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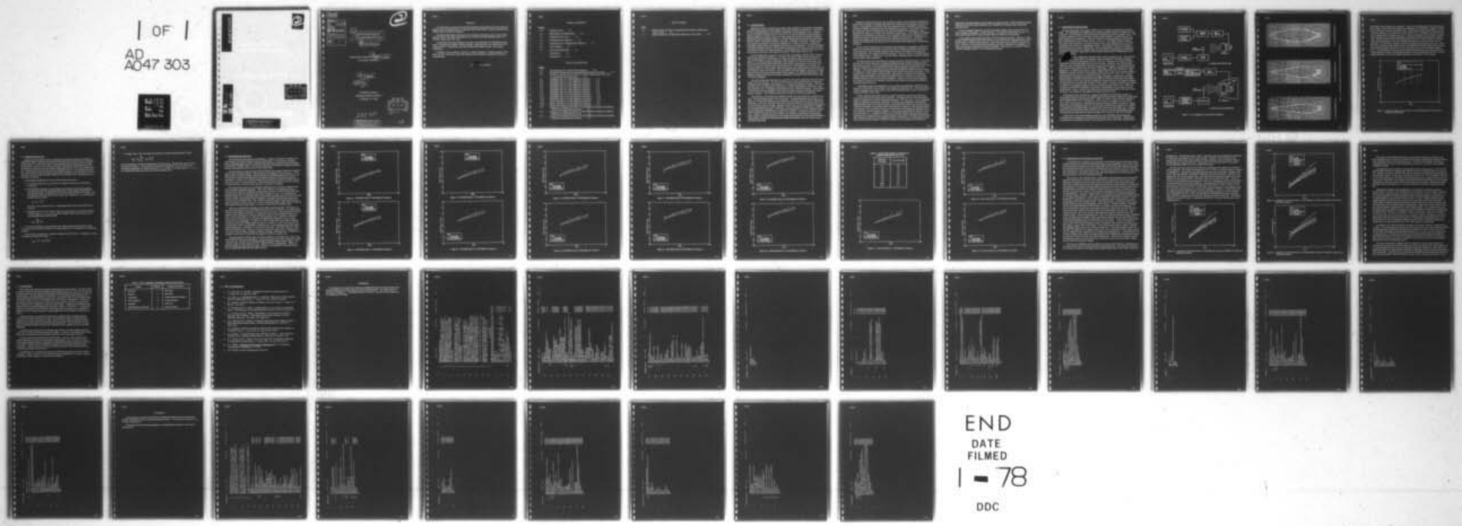

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PARAMETRIC SONAR STUDY NEAR-FIELD INVESTIGATION

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Dr. James C. Lockwood

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PREFACE

The opportunity to perform this Nearfield Parametric Sonar Study was made possible by adding a series of measurements to a Special Purpose Sonar (SPS) Transducer Measurement Program that was already in progress.

Nearfield measurements were made at the Transducer Evaluation Center, Naval Ocean Systems Center, San Diego, California and at the Naval Underwater Systems Center Test Facility, Seneca Lake, New York.

I am grateful to the help extended to me both in collecting data and critiquing this report by Dr. George Walsh, Messrs. William Backman, James Bartram, and Dennis McCrady of Raytheon; and Dr. Mark Moffet of the Naval Underwater Systems Center, New London, Connecticut.

In addition I wish to thank Mr. Herbert C. Single of Raytheon, Program Manager of this study, and Mr. John Neely, Code 06H1 NAVSEA, who authorized and funded the work that was performed.

Dr. [illegible] C. Lockwood

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

Difference frequency sound pressure levels in the nearfield of a parametric transmitting array have been measured in two separate experiments with the same projector. The projector has a nearfield distance at the primary frequencies of approximately 6.0 m. Measurements were made at ranges of from 3.0 to 24.0 m, in order to show the nearfield buildup of apparent difference frequency source level from within the projector's nearfield to approximately four times its nearfield distance. The first experiment took place at the Naval Ocean Systems Center's TRANSDEC facility in San Diego, California in July 1976. Measurements were made at ten difference frequencies ranging from 1.0 kHz to 12.0 kHz. In these and succeeding measurements, the projector was driven at two frequencies. The lower frequency remained a constant 42.58 kHz, and the higher frequency was varied from 43.58 to 54.58 kHz to produce the desired difference frequency. The downshift ratio, defined as the ratio of the mean primary frequency to the difference frequency, varied from 43.08 to 4.05.

The data obtained at a range of 24.0 m and some of the higher-frequency data at shorter ranges were considered satisfactory. However, the shorter-range, lower-frequency data were contaminated by receiver distortion, which was apparent from the shape of the beampatterns. It is believed that the hydrophone used, because it is of the electrostrictive type, has an inherent intermodulation distortion response that is proportional to the square of the primary frequency pressure at the measurement point. If the dependence on primary frequency pressure is in fact quadratic, then the distortion level must increase at a rate of 40.0 dB per decade as range is decreased. Thus a hydrophone showing negligible distortion at ranges greater than 24.0 m may be totally unusable at short ranges or at large downshift ratios. This suggests a fundamental limit to the useful combination of downshift ratios and nearfield range for a given hydrophone.

The second experiment took place in April 1977 at the Naval Underwater Systems Center's Seneca Lake Test Facility. The objective of the Seneca Lake experiment was to repeat the conditions of the TRANSDEC experiment and to overcome the distortion problem. The distortion was hoped to be eliminated by substitution of a different hydrophone, preferably, a non-electrostrictive one. If changing the hydrophone failed to resolve the problem, it was planned to cover the face of the hydrophone with a sound absorbing material to attenuate the intense primary radiation. The distortion would then be expected to diminish quadratically.

The objective of overcoming the distortion problem was not realized for a number of reasons. The major obstacle was a lack of test time. The nearfield measurements were to be taken as a low-priority addition to a test program in which the emphasis was on farfield measurements. In the end, only about three hours became available for nearfield measurements out of over three weeks of testing. Because of lack of time, it was not possible to attempt the use of a sound absorber to cut the distortion. It was not possible to obtain use of a suitable non-electrostrictive hydrophone, so the best that could be done was to use a different electrostrictive hydrophone and hope that it would be less nonlinear. Such did not prove to be the case. However, because time was so short it was decided to concentrate on taking axial levels and not to take beampatterns for all ranges and frequencies as was done at TRANSDEC. Consequently, the degree to which distortion affected the Seneca Lake test results was not determined until later.

Because no distortion-free data set was obtained, efforts were directed at evaluating the data that were obtained to establish which data were reliable and see if the data could be corrected. It was apparent for example, that the beampatterns from TRANSDEC revealed by their shape whether a substantial amount of distortion was present. It was further noted that the signal level could be estimated from the distorted beampatterns by fairing in a more characteristic shape in the vicinity of the maximum response axis. The method of identifying distortion and estimating corrections from the beampattern shape was not regarded as very satisfactory because it relied too heavily on the judgment of the observer. Furthermore, it could not be applied to the data taken at Seneca Lake because patterns were not made. Methods of estimating the distortion level and correcting the data analytically were therefore examined.

By use of the assumptions that the distortion level dependence is quadratic, and that the distortion and signal add in phase, it has been possible to deduce the distortion levels and to correct the data. The corrections depend to some extent on assumptions made about the range dependence of the signal as predicted by theory. However, there is no reliance on predicted absolute levels. Furthermore, only the shortest range data point is seriously affected by the assumed range dependence.

The data from the two experiments are compared with two nearfield theories. Then these two and several other theories are compared among themselves and their similarities and differences are noted. The first published theoretical treatment of the parametric array nearfield was included in the more general numerical volume integration model of Muir and Willette[1]. The volume integration program originally developed by Willette has been revised by Lockwood to include finite-amplitude effects and to improve numerical convergence. In its modified form, the program was used by Muir, Mellenbruch and Lockwood[2] to model the unusual nearfield geometry of the reflected parametric array. Lockwood's version of the Willette program is used in the present investigation. However, for the cases considered, the results are believed to be identical to those that would have been obtained had Willette's original program been used.

An analytical model of the parametric array nearfield was published by Berktay[3] in the same year (1972) that the Muir-Willette work appeared in published form. Because Berktay's model is applicable only to parametric arrays with collimated primary waves, it will not be considered further in this work.

In 1974, Bartram and Fugitt[4] reported a simple closed-form model for a parametric array with conical piston beam primary radiations. Assumptions used in that work include neglect of absorption and of finite-amplitude attenuation. The same year, a more complicated analytical model was reported by Lockwood[5]. Presented as an adaptation of the (farfield) Mellen-Moffett[6] model, the Lockwood model uses geometrically derived correction factors to modify the amplitudes of secondary signals emanating from ranges for which nearfield effects are important. The correction factors are derived under the assumption of negligible losses in the interval to which the factor is applied. Losses occurring outside that interval are properly accounted for. A significant feature of the Lockwood model is that it accounts for the transition from a conical beam to a cylindrical beam at the primary frequency nearfield limit. Other models are based on the assumption of either a cylindrical or a conical primary beam. (The Bartram[4] model contains a cylindrical nearfield in its formulation, but its effect is

suppressed in an approximation used to obtain the reported result.) Both the Bartram and the Lockwood models have been evaluated for the conditions of the Seneca Lake experiments reported herein.

In 1975, Rolleigh[7] published a nearfield model that includes explicit account of the primary frequency beampattern. In other respects, it is similar to the Bartram[4] model. Its major shortcoming is that it does not apply within the nearfield of the projector.

In two recent works, nearfield absorption has been taken into account. The first, a 1975 work of Mellen[8] actually contains two models, one for cylindrically collimated primary waves and the other for conical beam primaries. Both models have been evaluated in the present work. However, for the parameters considered, the effect of attenuation is negligible. The most recent model reported is by Mellen and Moffett[9]. This model is, in concept, closely related to Rolleigh's model[7], but is evaluated numerically.

2.0 EXPERIMENT DESCRIPTIONS

The two experiments, the results of which are to be reported, both took place in fresh water. The experiments at TRANSDEC were conducted with the projector at a depth of 5.44 m in the tank. A block diagram of the experimental arrangement is shown in Figure 2-1(a). The projector, effectively a 20-inch diameter circular piston transducer, radiated the two primary frequencies simultaneously. The lower frequency was held constant at 42.50 kHz and had a measured source level of 226.2 dB re 1 μPa at 1 m. The higher primary frequency was varied from 43.58 kHz to 54.58 kHz and had a source level varying from 221.3 to 227.8 depending on the projector's transmitting response. The signals from the two oscillators were summed prior to power amplification. The receiving system consisted of an NUSC XU-1313 hydrophone followed by a lowpass filter and preamplifier and the standard TRANSDEC electronics. Output was channelled to a polar plotter, which produced beampatterns for all of the measurements.

The experimental configuration at Seneca Lake is shown in Figure 2-1(b). The projector, th[illegible] behind a sonar dome, was suspended from the Transducer Calibration Platform (TCP) barge at a depth of approximately 76.0 m. The TCP electronics are similar to those at TRANSDEC and the preamp/filter box used was the same. Therefore, the only important difference in the receiving system was the use of an F-50 hydrophone. The signal generation used at Seneca Lake differed from that used at TRANSDEC. Rather than adding two primary frequencies, a modulator was used to produce *single sideband* (f_2) plus carrier (f_1). Other differences were the operation of the projector behind a dome, and a more powerful amplifier producing a primary source level outside the dome of 233.8 dB re 1 μPa at 1 m. For the measurements, the dome was positioned at the angle resulting in minimum beam distortion. Measurements at TRANSDEC indicated that the effect of the dome at this angle was to attenuate the primary source level and that the difference frequency source level seemed to behave as it should for the corresponding reduction in drive power. Therefore, the effect of the dome is believed to be negligible except to reduce the effective primary source level. Unlike the procedure followed in the TRANSDEC experiments, beampatterns were not drawn for each measurement. Rather, the beam was peaked up on the hydrophone and the axial source level was noted. The reason for this change of procedure was lack of time.

As mentioned in the introduction, during the TRANSDEC experiment the presence of intermodulation distortion in the receiving hydrophone was noted at short ranges and low frequencies by examining the shapes of the beampatterns. Figure 2-2 shows a rather extreme example of this. Figure 2-2(c) is the 1.5 kHz pattern at 24.0 m and is representative of the normal appearance of the parametric nearfield beampatterns showing no effect of distortion. Figure 2-2(b) is the corresponding pattern at 6.0 m and shows considerable elongation at the pattern tip caused by the very high primary frequency levels in the area of the major lobe. In figure 2-2(a), the 3.0 m pattern, the primary levels have become so high that intermodulation distortion dominates the parametrically generated signal even in the area of the first sidelobes.

The presence of the intermodulation distortion in the TRANSDEC data provided the motivation for the acquisition of nearfield data during the Seneca Lake tests. Unfortunately, very little was accomplished at Seneca Lake because there was so little time available after

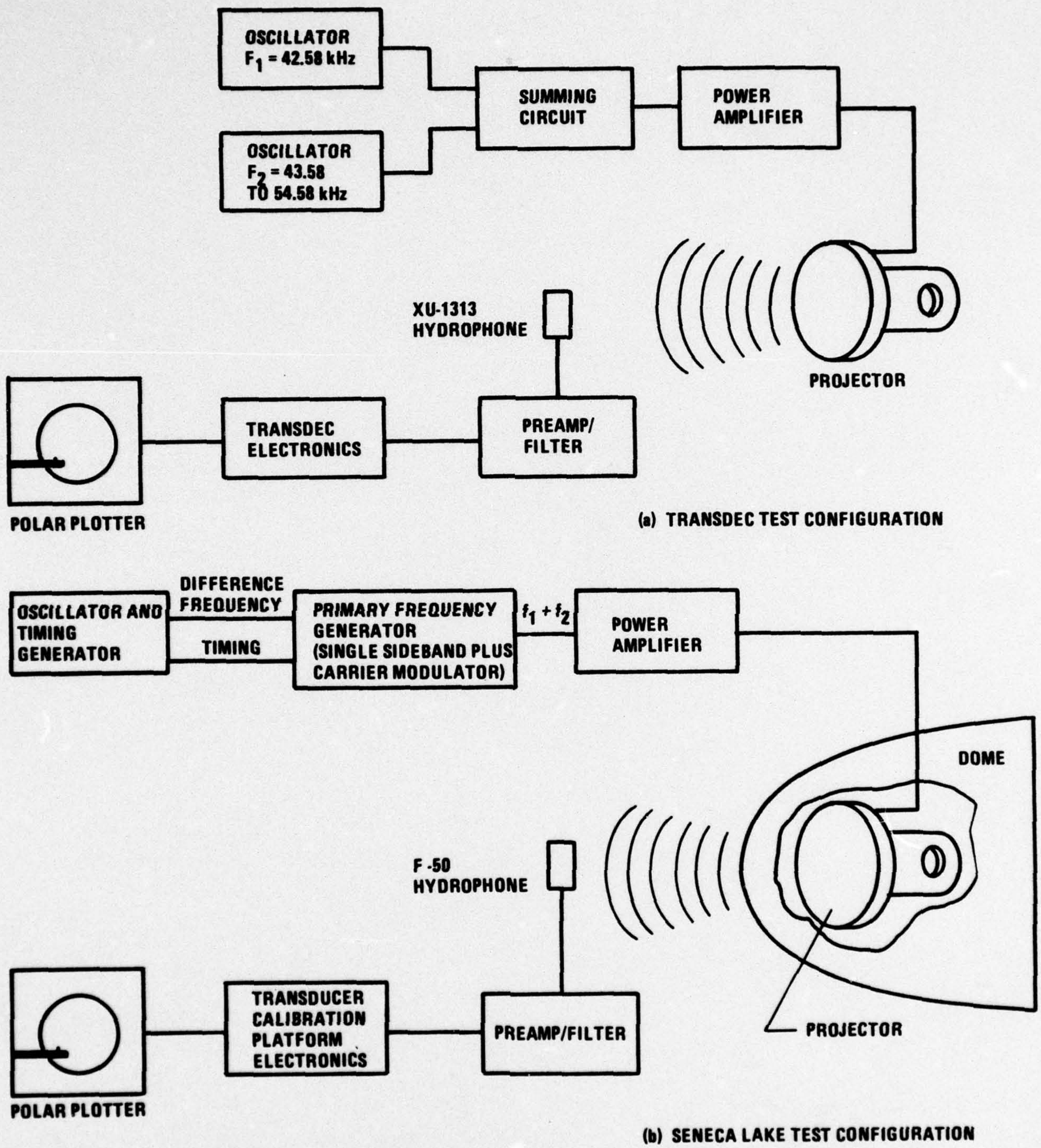
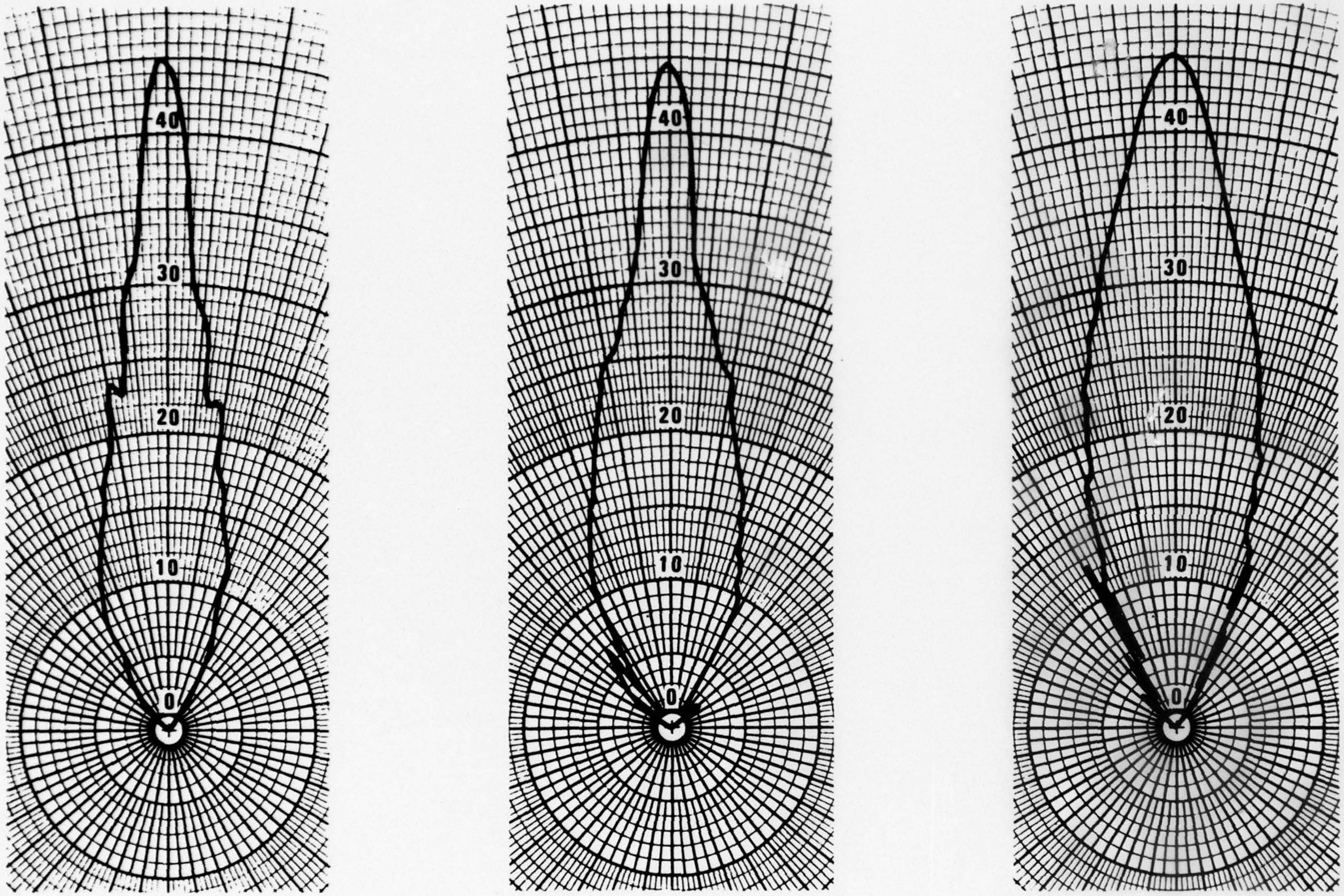


Figure 2-1. Test Configuration Functional Block Diagrams



(a) 1.5 kHz PATTERN AT 3.0 m

(b) 1.5 kHz PATTERN AT 6.0 m

(c) 1.5 kHz PATTERN AT 24.0 m

Figure 2-2. TRANSDEC Beampatterns Demonstrating Intermodulation Distortion

the farfield measurements were completed. There was one significant point demonstrated at Seneca Lake. That point was the power law dependence of the distortion. Figure 2-3 shows the 1.5 kHz data as measured at Seneca Lake. The data were taken at four primary source levels in 3.0 dB steps. The solid line is the theoretical curve according to the Muir-Willette[1] model evaluated for the highest source level. The great disparity between theory and experiment, particularly in the range dependence of the data, indicates that distortion is significant. The fact that the data for succeeding primary levels are almost exactly 6.0 dB apart shows that the dependence of the sum of signal and distortion on primary source level is quadratic. The parametric signal is known to be a quadratic function of primary level. Therefore, the fact that the range dependence does not change with primary source level indicates that the intermodulation distortion, is also a quadratic function of the primary frequency level. This demonstration that the intermodulation distortion goes as the square of the primary frequency pressure at the hydrophone makes it possible to attribute a 40.0 dB per decade range dependence to the intermodulation distortion in the farfield of the projector.

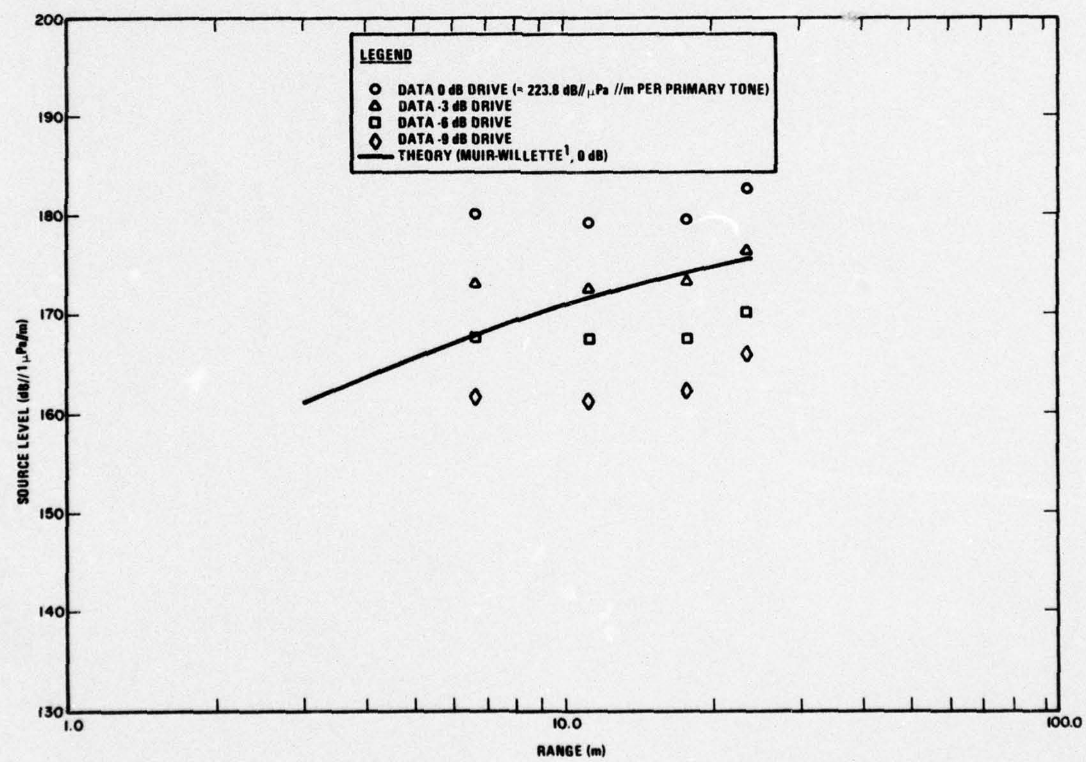


Figure 2-3. Secondary Frequency Source Level at 1.5 kHz as Measured for Four Drive Levels (Seneca Lake Experiment)

3.0 CORRECTION OF DATA

Because all of the data from the two experiments contain some amount of distortion, a method was sought to estimate the amount of error caused by the distortion and to perhaps correct the data. In order to do this, it was necessary to place some reliance on a theoretical model. However, this reliance was kept to a minimum by assuming that the theoretically derived levels for the two shortest range points had the correct ratio (difference in dB). Reliance on derived absolute levels was therefore avoided. The resulting corrected level for the shorter of the two ranges used is highly dependent on the theoretical ratio used. The other corrected values are quite insensitive to the assumed ratio, becoming less so as the range is increased.

The following assumptions were used in the correction procedure:

1) The measured pressure p_m is the sum of a signal pressure p_s and interference pressure p_I.

2) The interference pressure is proportional to the square of the primary pressure. The primary pressure is inversely proportional to range except in the nearfield. For nearfield points, the spherical wave correction given by Bobber[10] is used. With the nearfield correction expressed as a linear factor denoted by δ, the interference pressure may be written

$$p_I = p_{Io}\ \delta^2/r^2$$

Note that δ varies between 0 and 1, assuming the unity value in the farfield of the projector.

3) The signal levels at the two lowest ranges are proportional to the theoretical levels at those ranges, i.e., if p_{s1} and p_{s2} are the signal levels and p_{t1} and p_{t2} are the corresponding theoretical levels then

$$p_{s2} = \frac{p_{t2}}{p_{t1}}\ p_{s1}.$$

The two lowest ranges are used because they contain the greatest proportion of interference and hence the least sensitivity to the actual signal level in estimating the interference pressure.

With the above assumptions, a system of equations may be written. At range 1 (eg. 3.0m) the measured pressure is written

$$p_{m1} = ps1 + p_{Io}\ \delta_1^2/r_1^2.$$

At range 2 (eg. 6.0m), the measured pressure is written using assumption 3 above,

$$p_{m2} = p_{s1} \frac{p_{t2}}{p_{t1}} + p_{Io}\, \delta_2^2 / r_2^2 .$$

For each frequency, the above equations can be solved for p_{Io}, which is then used to correct the data at all ranges. The only nearfield range point considered is the 3.0m point in the TRANSDEC experiment, for which the value of δ_1, is 0.8224. In all other cases, $\delta_1 = \delta_2 = 0$. The Lockwood[5] model was used to provide the theoretical ratio.

4.0 EXPERIMENTAL RESULTS

The experimental data obtained at TRANSDEC are plotted in Figures 4-1 through 4-10. In each figure the measured data are shown as solid circles. The solid line represents theory calculated using Lockwood's model[5] and the dashed line represents theory calculated from the Muir-Willette[1] model. The crosses represent corrected data, calculated assuming that the Lockwood theory has the correct short range slope.

The two theories are shown because they demonstrate the contrast between the results of different types of approximations. Other theories are compared in the next section. At the larger ranges it would be initially expected that the Muir-Willette model would be more correct than the Lockwood model because of the explicit inclusion of the primary frequency beampattern. However, for reasons discussed in the next section, the Muir-Willette results may be as much as 1.0 dB conservative. The Lockwood model is expected to be more correct at ranges below 6.0 m because of the inclusion of a planewave nearfield.

The source levels used in the TRANSDEC experiments were easily low enough to make finite-amplitude attenuation negligible. Under such conditions, the secondary pressure increases as the square of the primary pressure and for every 1.0 dB of increase in the mean primary source level the secondary source level increases 2.0 dB. For convenience the theoretical data were all calculated using a mean primary frequency source level of 227.8 dB// μPa//m, and the measured data shown in Figures 4-1 through 4-10 have been scaled up by twice the source level difference. The amounts by which the levels at each frequency have been increased are shown in Table 4-1. In a few cases more than one data value was obtained. These generally agreed within about 1.0 dB and are shown here as average values.

There is a considerable variability in which theory best fits the data. When there is a theoretical discrepancy of 2.0 dB it is difficult to resolve even by distortion free measurements because of the quadratic dependence on the primary source level. The test facilities are considered to have accuracies of about ±1.0 dB and a 1.0 dB error in estimating the primary frequency source level leads to a 2.0 dB error in the secondary level. In any case, Figure 4-1 shows corrected data that are very close to the dashed Muir-Willette[1] curve, the solid Lockwood[5] curve being higher. In Figure 4-2, the 12 m data point is not really consistent but otherwise the Muir-Willette theory is favored. In Figure 4-3, the 3.0 m point was discarded because it led to unreasonable corrected levels. The remaining points tend to agree with the dashed line. In Figure 4-4, the solid line is favored. The data in Figure 4-5 also favor the Lockwood curve. Figure 4-6 does not really favor either curve. It appears that in this case, the correction procedure resulted in too high a distortion level. In Figures 4-7 through 4-10 the trend is toward data that support both theories equally well.

The data obtained at Seneca Lake are shown in Figures 4-11 through 4-13. Here, data were obtained at only three frequencies. The primary source level was a constant 233.8 dB// μP//m per tone, still too low for significant finite-amplitude effects at these ranges. The minimum range for these data was 6.74 m, limited by the test configuration. There is a general tendency for these data to be high. They give a reasonable fit to the solid curves, but are significantly higher than the dashed curves.

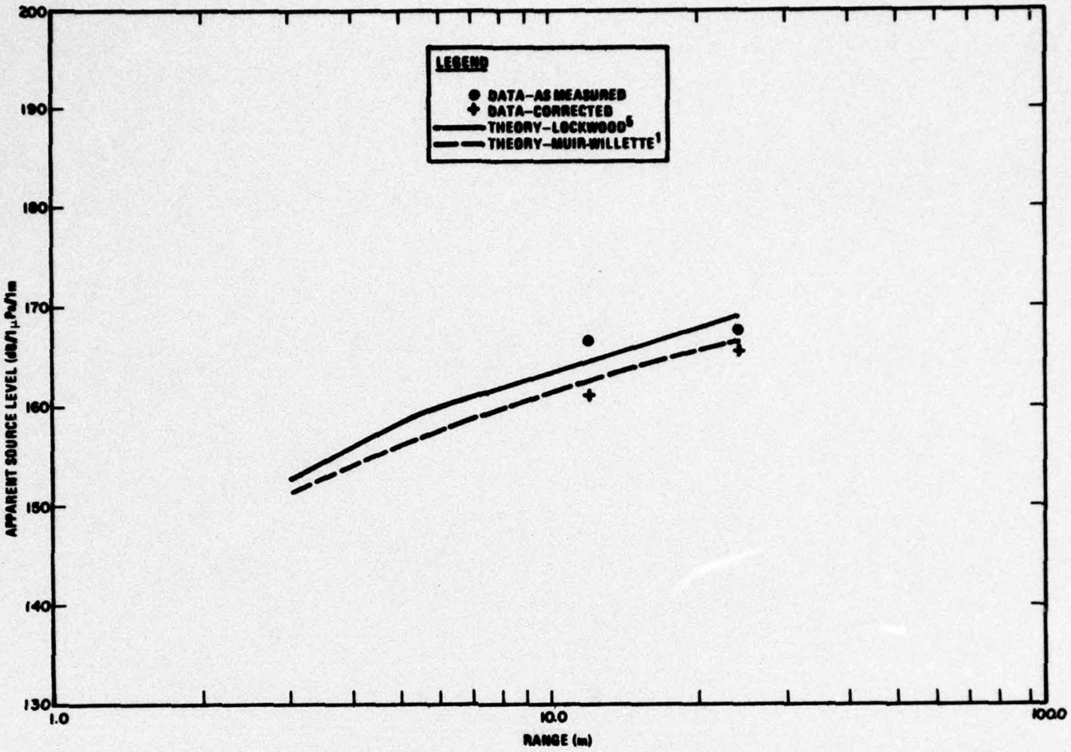


Figure 4-1. TRANSDEC Data at 1.0 kHz Difference Frequency

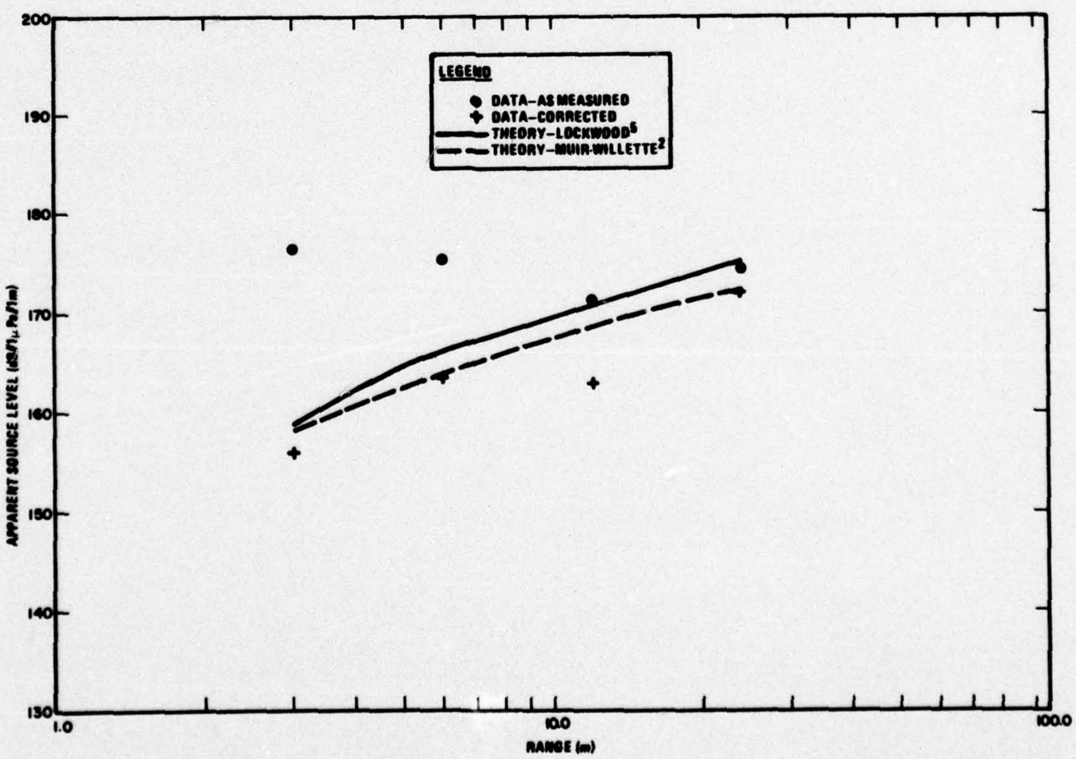


Figure 4-2. TRANSDEC Data at 1.5 kHz Difference Frequency

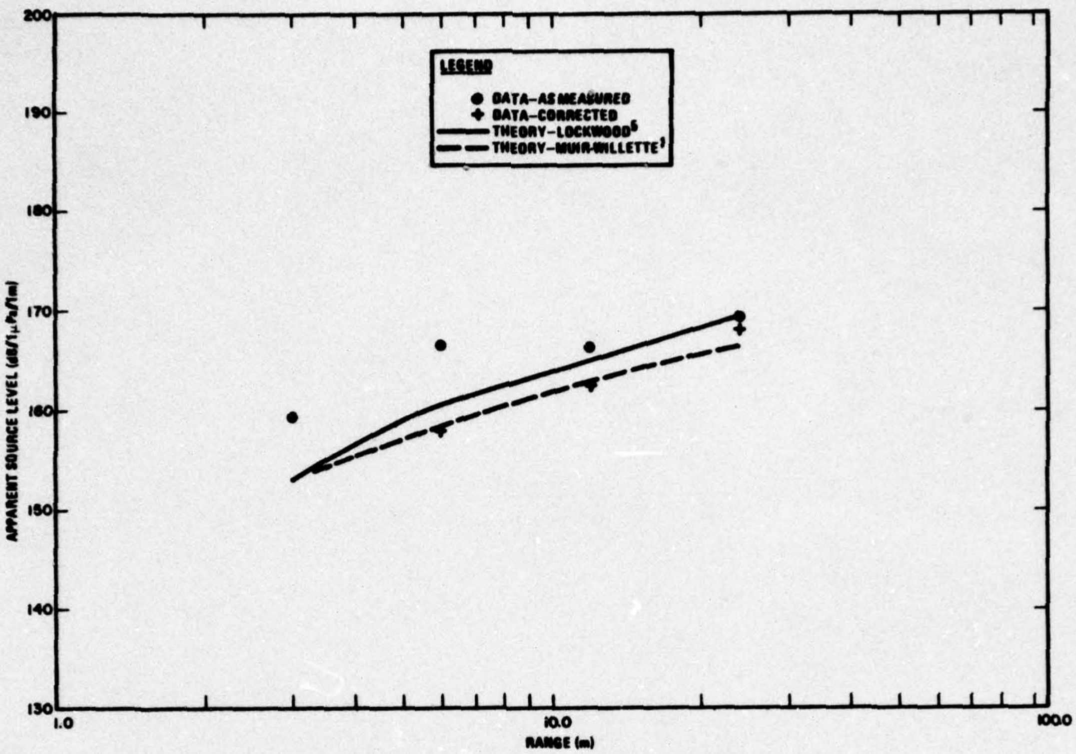


Figure 4-3. TRANSDEC Data at 2.0 kHz Difference Frequency

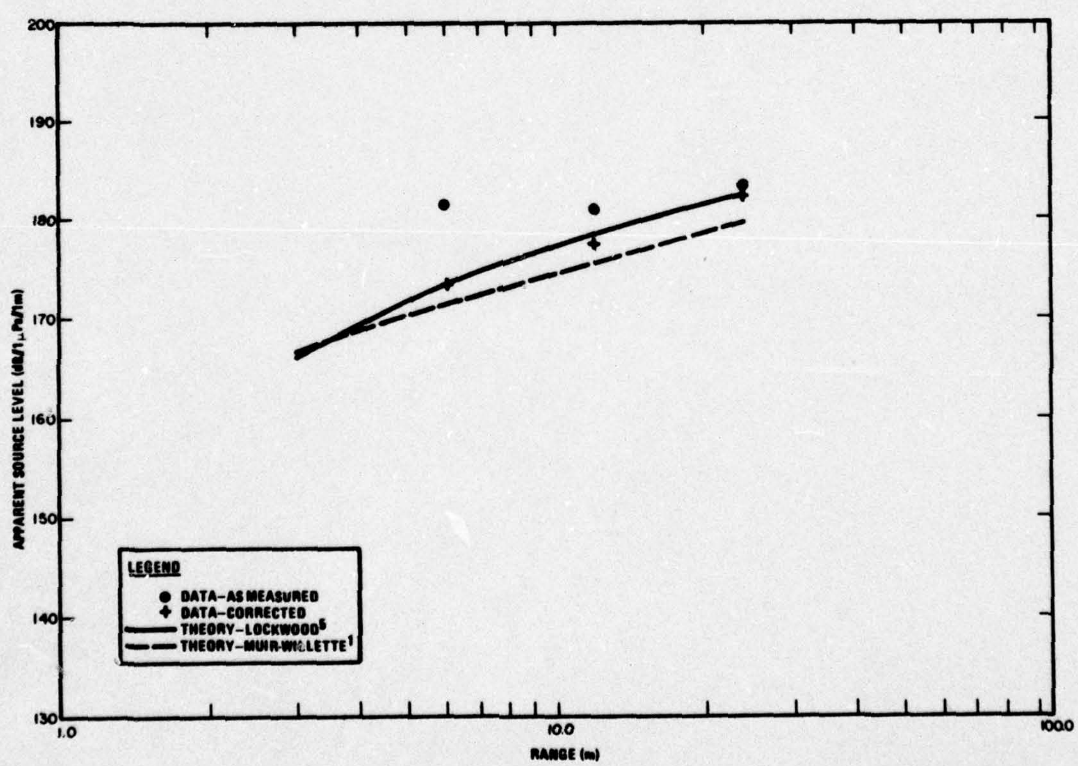


Figure 4-4. TRANSDEC Data at 2.5 kHz Difference Frequency

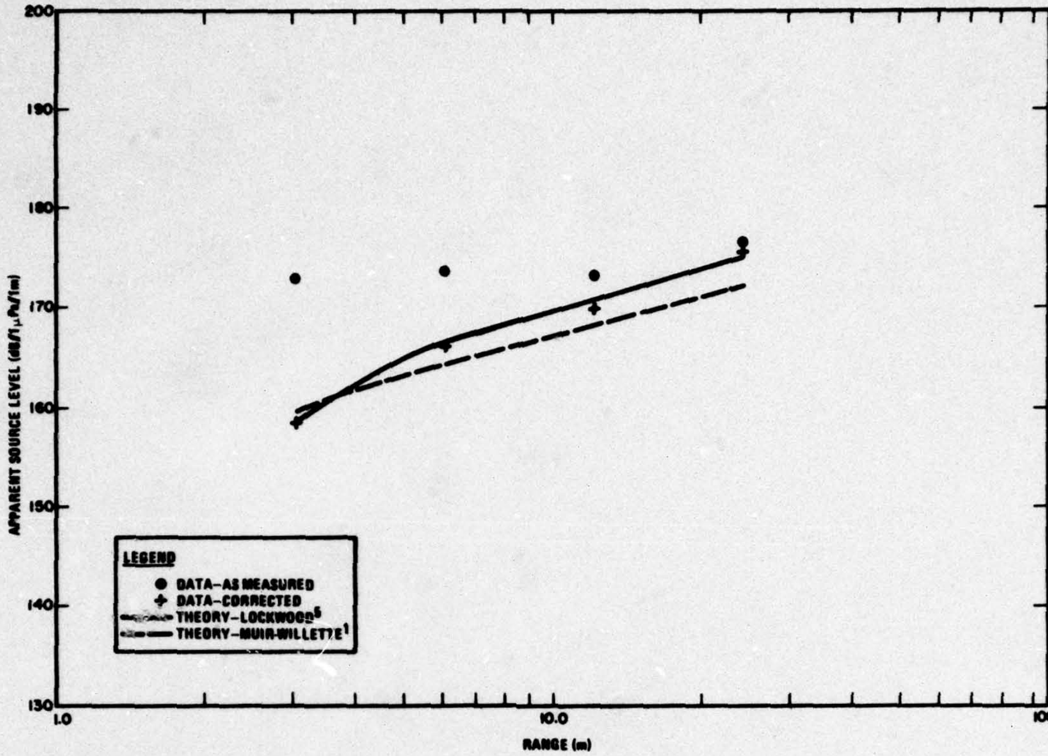


Figure 4-5. TRANSDEC Data at 3.0 kHz Difference Frequency

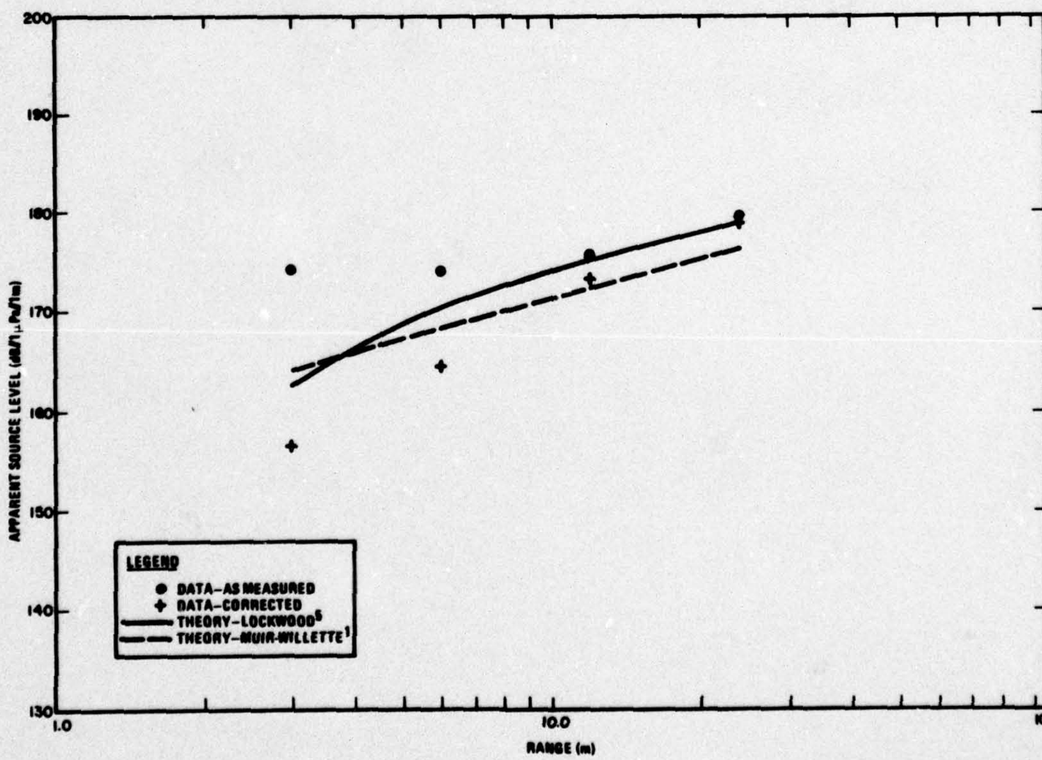


Figure 4-6. TRANSDEC Data at 4.0 kHz Difference Frequency

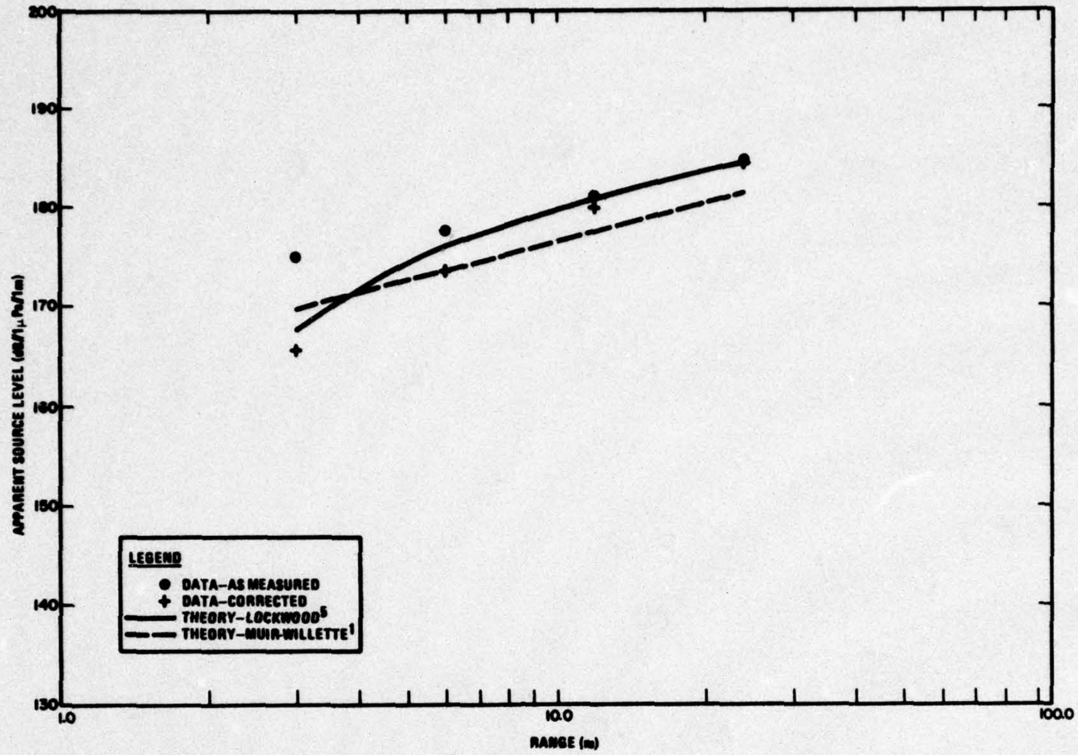


Figure 4-7. TRANSDEC Data at 6.0 kHz Difference Frequency

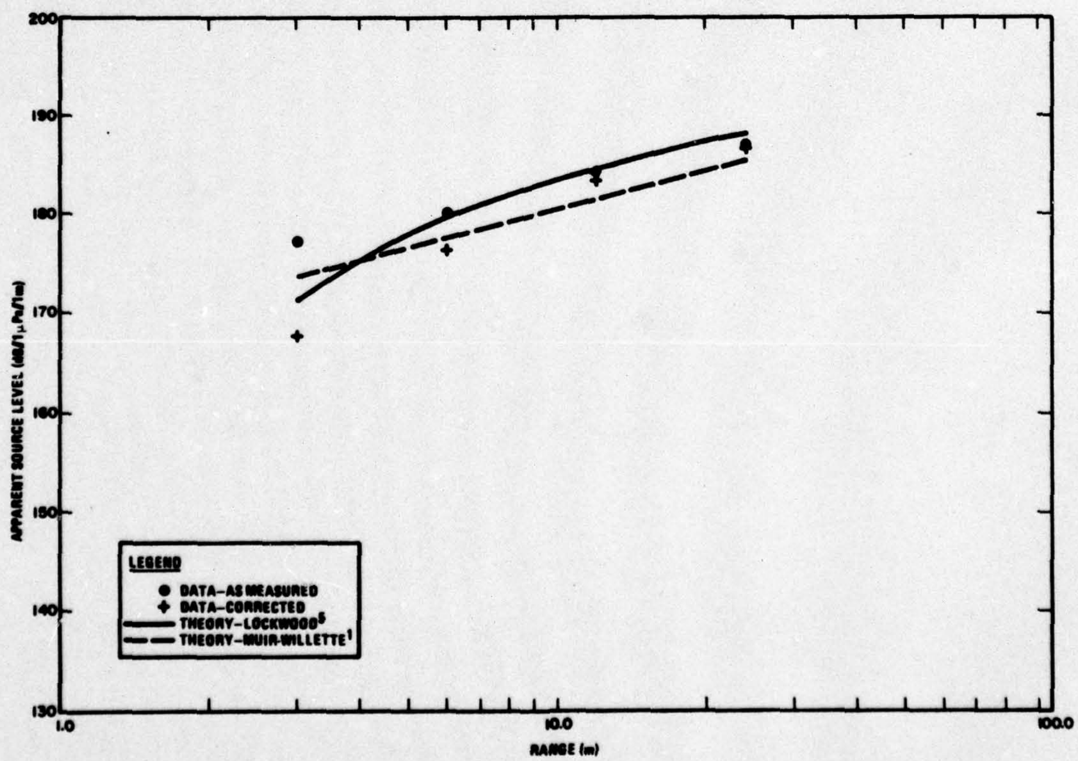


Figure 4-8. TRANSDEC Data at 8.0 kHz Difference Frequency

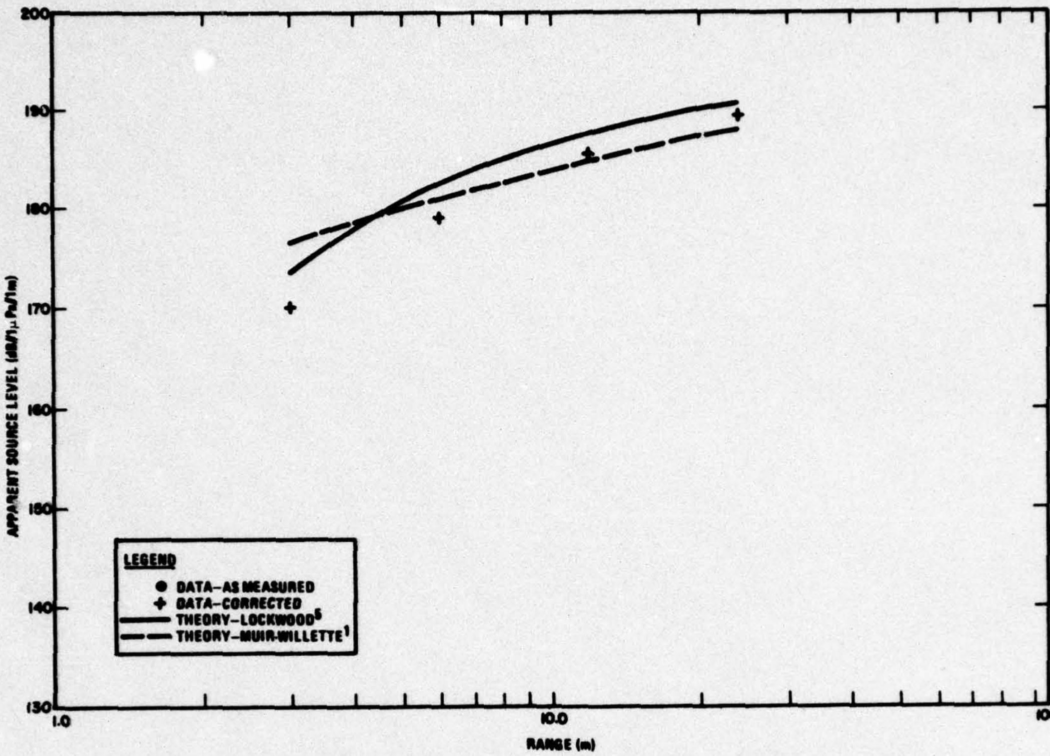


Figure 4-9. TRANSDEC Data at 10.0 kHz Difference Frequency

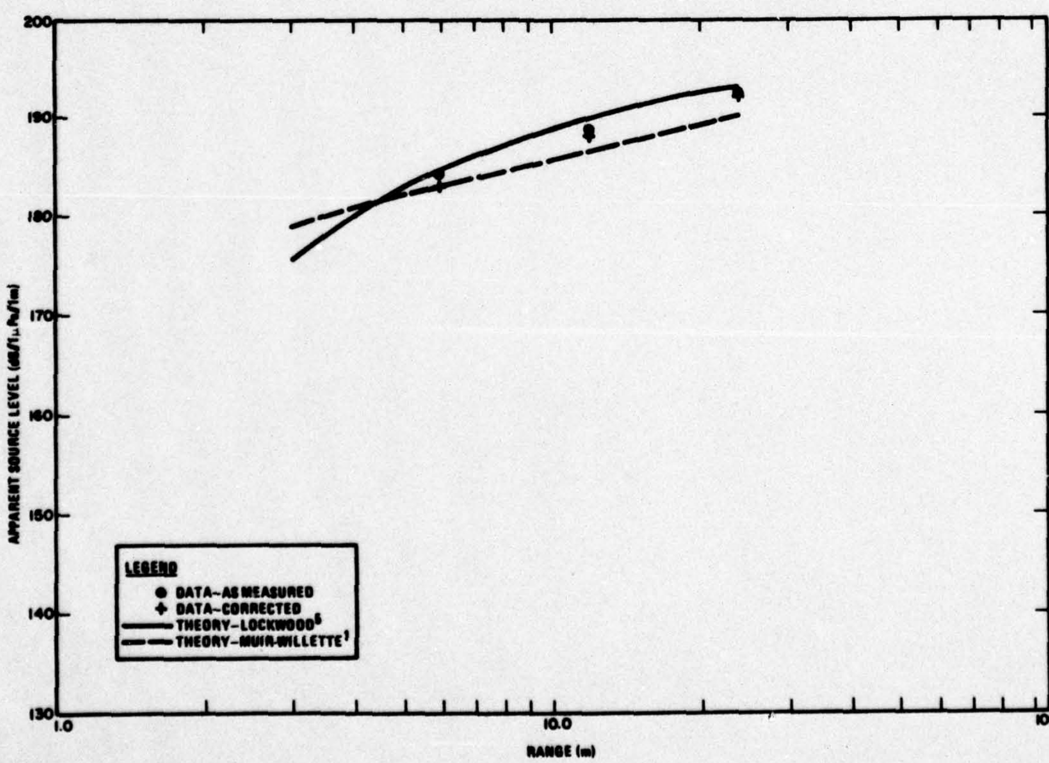


Figure 4-10. TRANSDEC Data at 12.0 kHz Difference Frequency

Table 4-1. Measured Data Increases to Compensate for Assumed Constant Mean Source Level

Difference Frequency	Correction (dB)
1.0	2.2
1.5	1.8
2.0	1.6
2.5	1.6
3.0	1.9
4.0	1.9
6.0	4.6
8.0	6.0
10.0	7.5
12.0	8.1

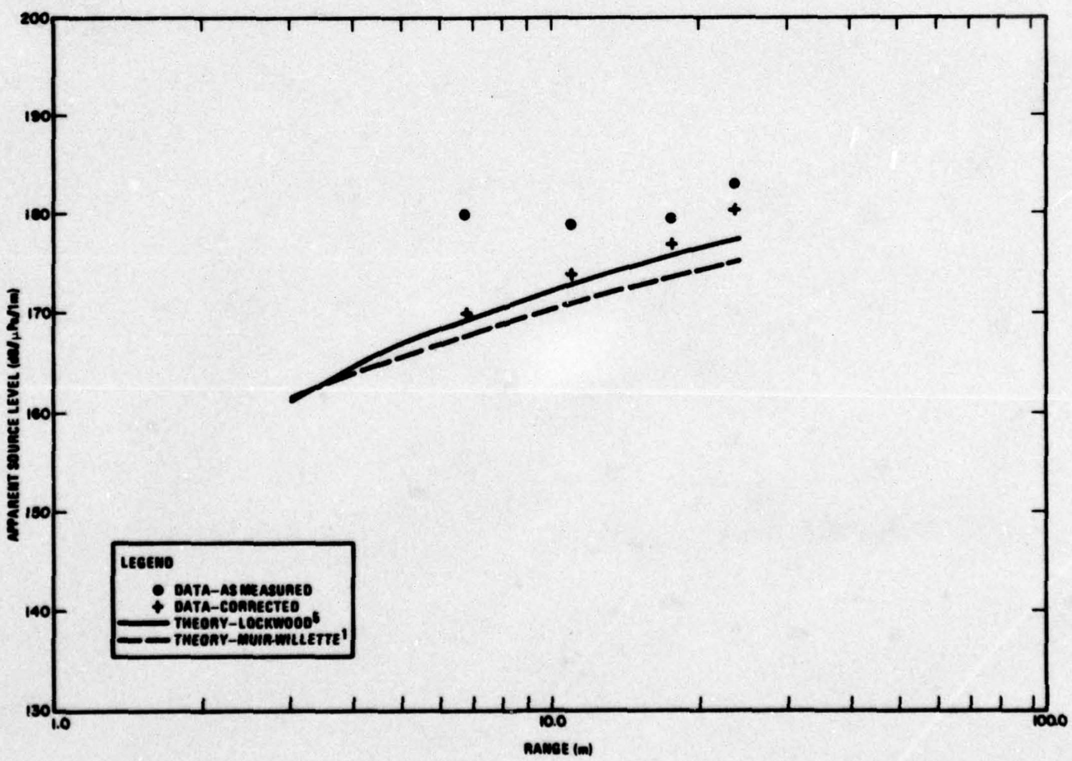


Figure 4-11. Seneca Lake Data at 1.5 kHz Difference Frequency

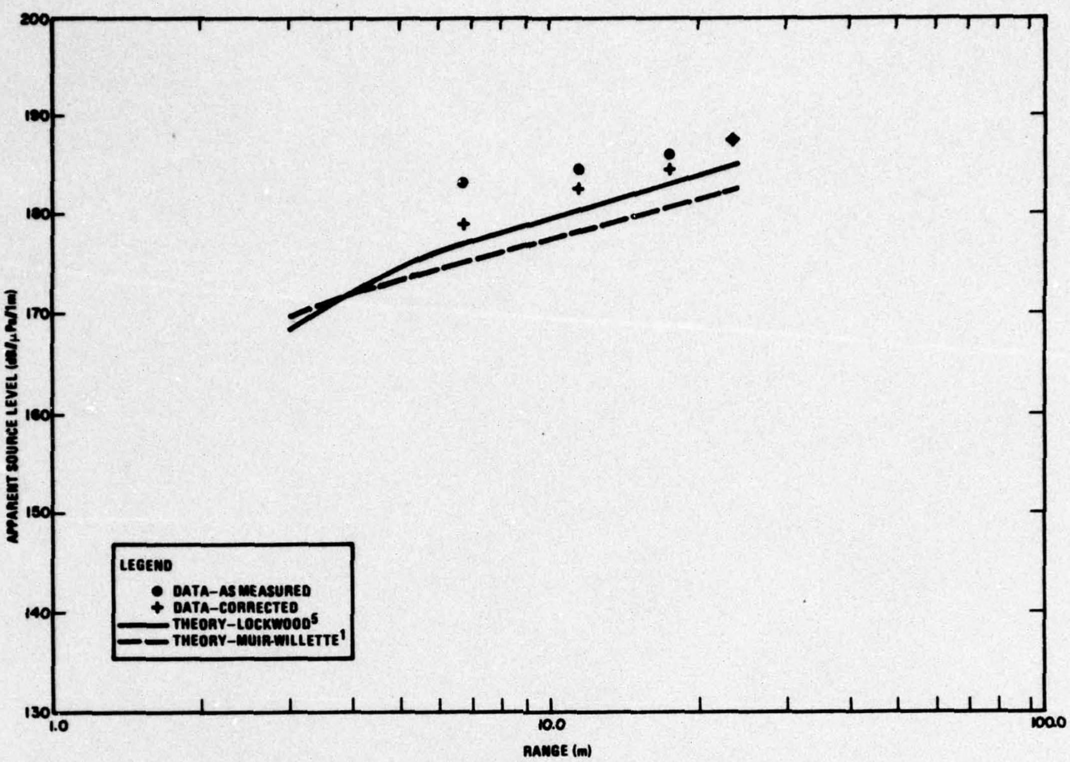


Figure 4-12. Seneca Lake Data at 2.5 kHz Difference Frequency

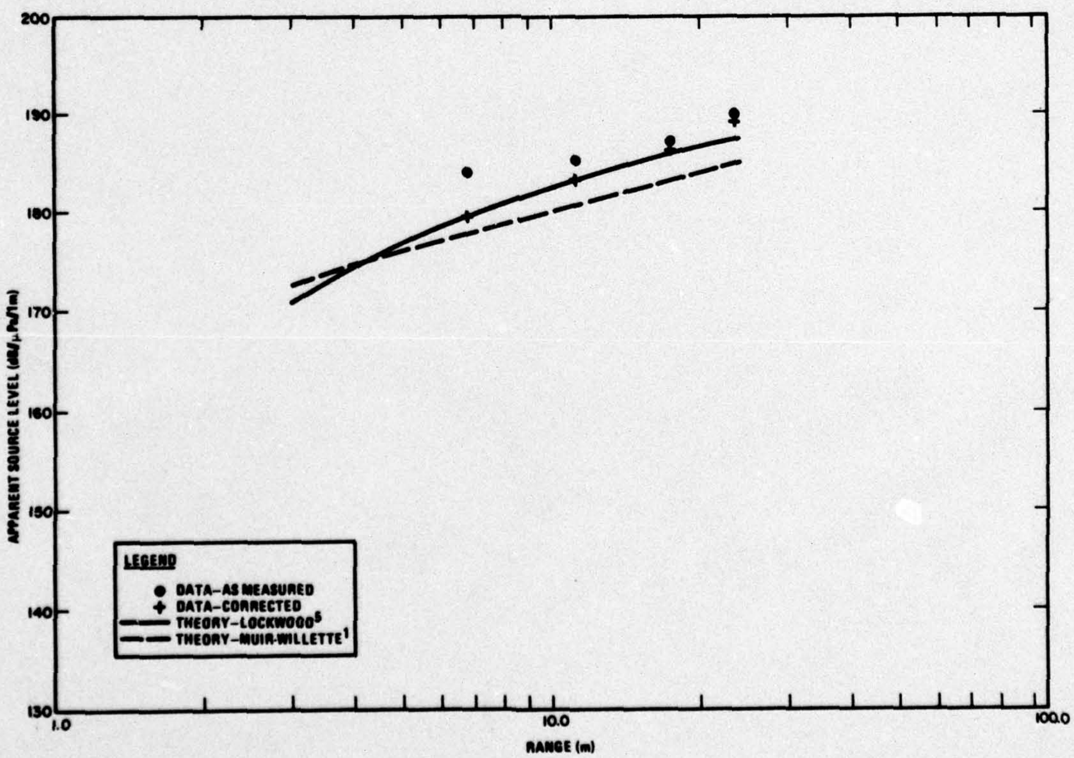


Figure 4-13. Seneca Lake Data at 3.0 kHz Difference Frequency

5.0 COMPARISON OF THEORETICAL RESULTS

A convenient way of looking at the parametric array nearfield has the interaction volume divided into apertures formed by slicing the primary beam perpendicular to its acoustic axis. Each such aperture radiates secondary signals with a farfield level that depends on the amplitude and phase distribution of the source strength density in the aperture and on the distance from the aperture to the measurement point. Each aperture also has a nearfield. The amplitude and phase at a measurement point is the sum of the signals from all of the apertures from the projector out to the measurement point.

The accuracy of any nearfield model, assuming that loss mechanisms may be neglected, depends on the accuracy with which the primary field is modeled and on the accuracy with which the contributions of all the virtual sources are summed at the measurement point. Most of the nearfield models that have been proposed treat the primary beam as a spherically spreading wave retaining the assumed farfield characteristics all the way back to the source. The exceptions are the strictly cylindrical-beam models such as those of Berktay[3] and of Mellen[8], and Lockwood's model[5], which combines a planewave nearfield and a spherically spreading farfield. The conical beam models are not applicable to measurement points in the primary beam's nearfield. Another issue concerning the description of the primary beam is the assumed beampattern. In the models of Bartram[4], Mellen[8] and Lockwood[5], the farfield beam is assumed to be conical, with equal amplitude over a spherical cap, and with energy equal to the total radiated energy. A description that is, in principle, more precise incorporates the theoretical beampattern of the projector. The Muir-Willette[1], Rolleigh[7] and the new Mellen-Moffett[9] nearfield models are examples of this type of treatment. It turns out that there is generally a discrepancy of about 2.0 dB for cases considered in the present work between models incorporating the primary beampattern and those not. This is because the major lobe of the circular piston pattern accounts for only about 80% of the radiated energy. While the assumption that 100% of the primary frequency energy contributes to the secondary source strength clearly represents an upper bound, the models that incorporate the beampattern tend to be conservative for two reasons. First, they all assume that the primary beampattern applies all the way back to the source. It seems reasonable to expect 100% of the primary frequency energy to contribute in the projector nearfield because the sidelobe energy is still in the column. The second reason is that it is usual to assume that negligible signal comes from outside the major lobe. In the Muir-Willette model[1], for example, the integration over angle is only carried out to the first null of the primary pattern. Yet, in nearfield cases, energy from the sidelobes may be significant. A preliminary test of the Muir-Willette model in which the angle included in the integration was quadrupled showed an increase of about 0.3 dB for cases of present interest. From the two reasons combined, the models may well be low by as much as 1.0 dB at 24.0 m and even more at shorter ranges that are still in the projector farfield.

There are two significant issues related to the accuracy with which the contributions of all of the virtual sources are summed at the measurement point. The most basic consideration is that the variation of the range from the measurement point to each virtual aperture be

accounted for. All nearfield models do this. The other issue is the handling of the apertures for which the measurement point is in the nearfield. Because of their proximity to the measurement point, phase varies rapidly over these apertures, and care should be taken to see that they are properly described. The accuracy of the various models in this regard and the quantitative effect of errors are difficult to assess.

Six of the theories discussed above have been evaluated for the conditions of the Seneca Lake experiment. The results for frequencies of 1.5, 3.0 and 10.0 kHz are shown in Figures 5-1 through 5-3. The theories represented by lines are those of Bartram[4], Rolleigh, Lockwood[5], Muir and Willette[1], and Mellen[8] (cylindrical and conical versions). Because of the assumptions of a conical primary beam, none of the theories shown are expected to be valid within 6.0 m except for the Mellen[8] cylindrical model and the Lockwood[5] model. These two models are in reasonable agreement between 3.0 and 6.0 m, although the Lockwood model appears to be relatively low at the 10 kHz frequency. If one discounts the Mellen cylindrical model beyond 6.0 m, then all of the theoretical results fall within about 3.0 dB at 1.5 kHz, 3.5 dB at 3.0 kHz and 4.5 dB at 10.0 kHz. The increase in spread appears to be attributable solely to a drop in the Muir-Willette[1] curve relative to the others. However, on close inspection, it is observed that the Muir-Willette[1] and Lockwood[5] theories appear to retain a constant ratio as frequency is varied Also, the Bartram[4] and Rolleigh[7] theories tend to keep the same ratio but to change relative to the Muir-Willette and Lockwood theories. The Mellen[8] (conical) curve does not seem to consistently track either of the pairs of theoretical curves mentioned above.

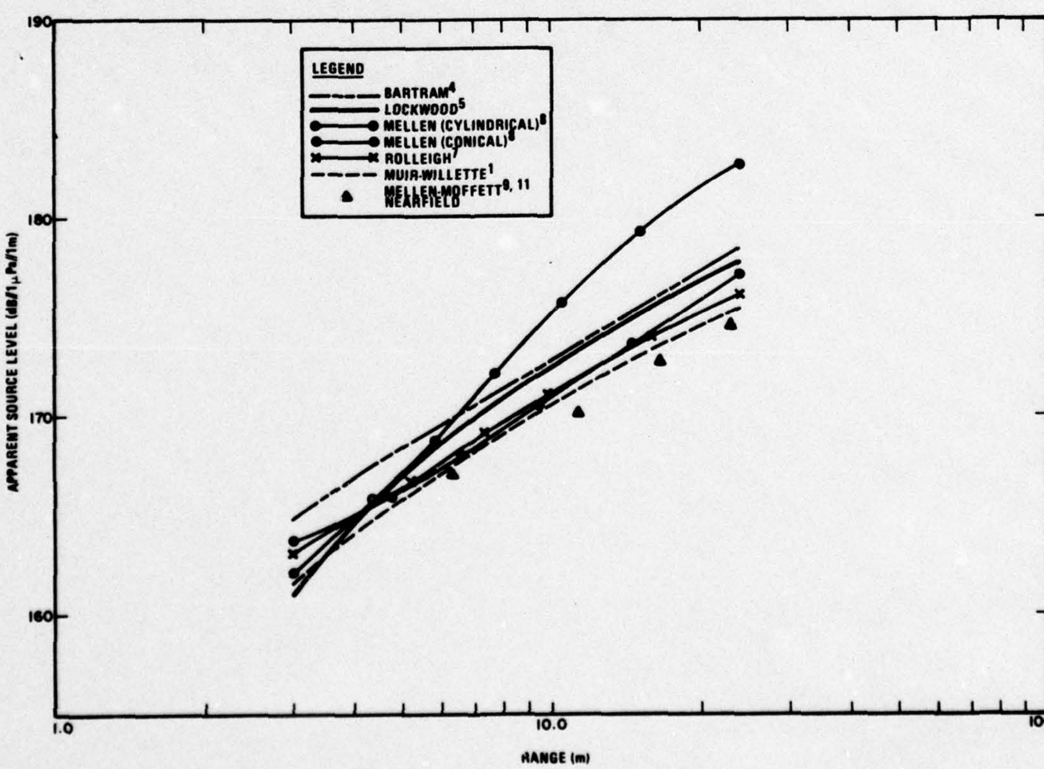


Figure 5-1. Comparison of Theoretical Data for 1.5 kHz Difference Frequency (Conditions of Seneca Lake Experiment Assumed)

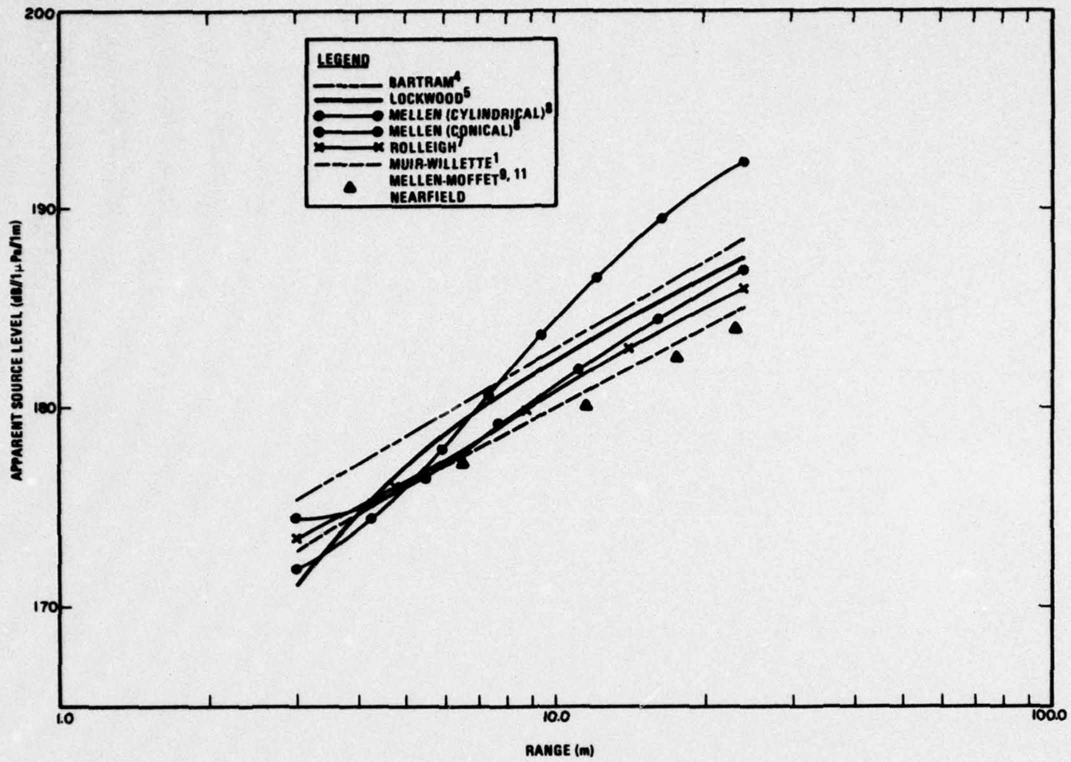


Figure 5-2. Comparison of Theoretical Data for 3.0 kHz Difference Frequency (Conditions of Seneca Lake Experiment Assumed)

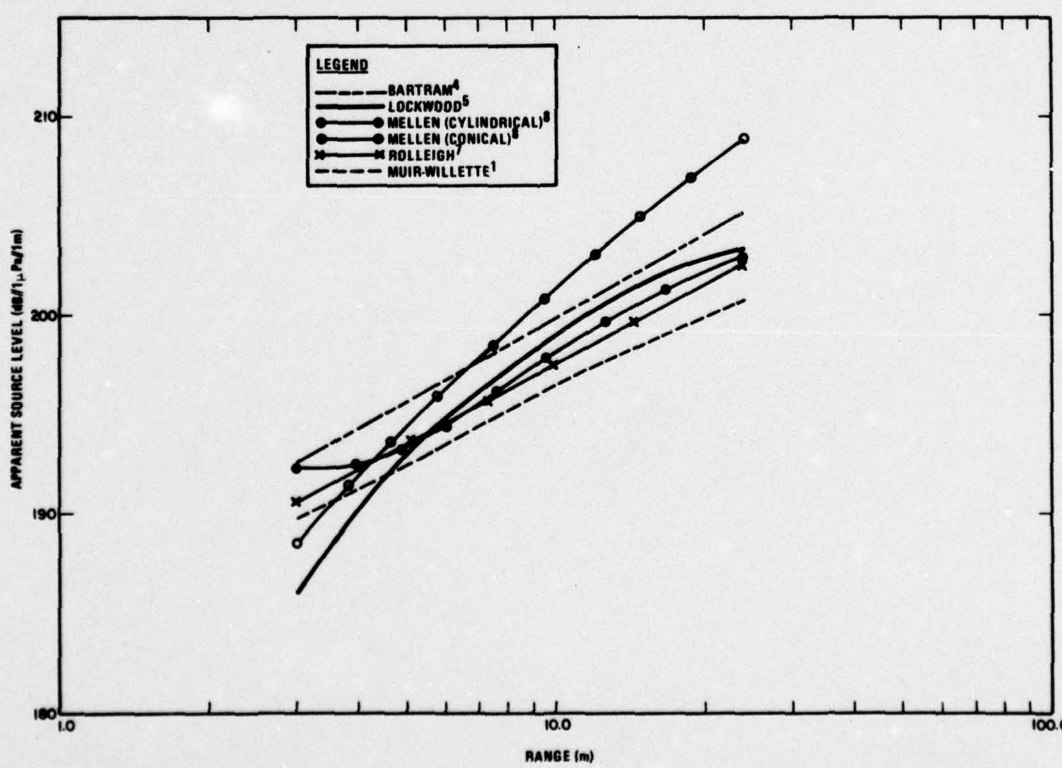


Figure 5-3. Comparison of Theoretical Data for 10.0 kHz Difference Frequency (Conditions of Seneca Lake Experiment Assumed)

The reason for this shift with frequency of two theories relative to two others is not fully understood, but is believed to be related to the method of handling the apertures that are in the nearfield relative to the observation point. The shift at short ranges of the Mellen (cylindrical) theory relative to the Lockwood theory may also be related to the handling of nearfield apertures.

The offset between the Bartram[4] and Rolleigh[7] theories and between the Lockwood[5] and Muir-Willette[1] theories at ranges greater than the projector's nearfield distance is believed to be caused by the explicit account of the primary frequency beampattern in the Rolleigh and Muir-Willette models. In each case, the offset is about 2.0 dB. It is interesting to note that 2.0 dB is the approximate ratio of the total radiated energy to the energy in the main lobe for the projector considered. The Bartram and Lockwood models assume that all of the radiated energy goes into the interaction, whereas the models that incorporate a beampattern include little that is not in the major lobe. A 2.0 dB discrepancy is therefore consistent with this fact.

Although the inclusion of the beampattern is, in principle, more accurate than the simpler model, in practice, the results tend to be conservative. This is largely because of the use of the approximation that the primary beam is conical all the way to the origin. In the primary nearfield, it seems reasonable to expect all of the energy to contribute to the secondary signal, not just the 80% in the major lobe. In fact, it might be argued that all energy within the first Fresnel zone relative to the observation point should contribute. A further effect of using the theoretical beampattern that may lead to erroneous results is the non-ideal nature of the primary frequency beampattern. High sidelobe levels may increase the amount of energy contributing to the axial secondary signal. For conditions of the present experiments, the explicit inclusion of the primary frequency beampattern combined with the conical beam assumption is estimated to lead to results that are too low by a minimum of 0.5 dB at 24.0 m. An error of as much as 1.0 dB is not unlikely. Therefore, it appears that if two models were precisely correct in all respects except the handling of the primary beampattern, then the version with the theoretical beampattern included should provide a lower bound, the model assuming all radiated energy to occupy a constant amplitude cone should provide an upper bound, and the "true" value should lie in the middle.

In summary, all models considered are within 3.0 dB in their regions of applicability at 1.5 kHz. The spread among the results increase as frequency is increased, with the Bartram and Rolleigh data maintaining an approximately constant ratio and the Lockwood and Muir-Willette data maintaining an approximately constant ratio. In each case, the constant ratio is approximately 2.0 dB and can be attributed to the handling of the primary beampattern. The disparity between the Bartram and Rolleigh models on one hand and the Lockwood and Muir-Willette models on the other is unexplained, but is believed related to the handling of geometry close to the measurement point.

The data represented by triangular points on Figures 5-1 and 5-2 have been left for discussion at the end of the section because they were not evaluated by the present author and are not available at the entire span of ranges and frequencies considered. These data were supplied by Moffett[11] using parameters supplied by the author for the conditions of the Seneca Lake experiment. These data from the new Mellen-Moffett[9] nearfield model agree quite well with the Muir-Willette[1] results, but tend to be lower, in some cases by as much as 1.0 dB.

6.0 CONCLUSIONS

Results from two parametric nearfield experiments have been reported. The data, known to contain substantial receiving hydrophone intermodulation distortion, have been corrected by deducing the level of the distortion and coherently subtracting the distortion pressure from the measured data. The data obtained at TRANSDEC at ten frequencies support both the Lockwood[5] and the Muir-Willette[1] theories quite well. Note that the latter is not considered valid at ranges less than 6.0 m; so any disagreement in this region is disregarded. Because the data seem to support both theories equally well, they especially support the contention that the two theories are, respectively, upper and lower bounds. Comparison with other theories considered may be effected indirectly by referring to Figures 5-1 through 5-3. Although the figures were prepared for the conditions of the Seneca Lake experiment, the comparison of relative levels for a given frequency is equally applicable to the TRANSDEC experiment conditions.

When the theories are compared in light of the TRANSDEC data, it appears that the Bartram[4] theory has a tendency to be high. The Rolleigh[7] and Mellen[8] (conical) theories, in the primary farfield where they are valid, tend to lie between the Lockwood[5] and Muir-Willette[1] curves and so agree well with the experimental data. The fact that these models tend to shift with frequency relative to the Lockwood and Muir-Willette curves is somewhat disturbing.

The Seneca Lake data tend to be somewhat high relative to the Muir-Willette and Lockwood curves, giving a reasonable fit only to the latter. However, the conditions under which these data were obtained are such that little confidence can be associated with them.

A test of several nearfield theories has been made. Because of the condition of the experimental data, the test is not particularly discriminating. Also, there is not a great deal of spread among the theories considered. Within their regions of validity, the theories of Rolleigh[7], Mellen[8], Muir and Willette[1] and Lockwood[5] all give good agreement with experiment. Of these, the last is the only one that is uniformly valid at points in both the nearfield and farfield of the projector.

In conclusion, it is of interest to compare the difficulty of applying the various models considered. Table 6-1 gives for each model the degree of difficulty on a scale of 1 (easy) to 10 and the minimum equipment requirement for evaluation.

Table 6-1. Degree of Difficulty and Equipment Required for Each Model

Model	Difficulty	Equipment Required
Bartram[4]	1	Slide Rule
Mellen[8]	2	Slide Rule
Lockwood[5]	3	Programmable Calculator
Muir-Willette[1]	10	Large Computer
Rolleigh[7]	1	Slide Rule
Mellen-Moffett Nearfield[9]	10	Large Computer

7.0 LIST OF REFERENCES

1. T.G. Muir and J.G. Willette, "Parametric Acoustic Transmitting Arrays," J. Acous. Soc. Am. 52, 1481 (1972).
2. T.G. Muir, L.L. Mellenbruch and J.C. Lockwood, "Reflection of Finite-Amplitude Waves in a Parametric Array," J. Acous, Soc. Am. publication pending.
3. H.O. Berktay, "Nearfield Effects in Parametric End-Fire Arrays," J. Sound Vib. 20, 135 - 143 (1972).
4. J.F. Bartram and R.P. Fugitt, "Nearfield Effects in a Parametric Transmitting Array," 87th Meeting of the Acoustical Society of America, New York, April 1974.
5. J.C. Lockwood and D.P. Smith, "Investigation of the Increase in Parametric Efficiency Due to Bubbles, " Final Report under Contract N00024-74-C-1151, AMETEK, Straza Div., El Cajon, CA, August 1974.
6. R.H. Mellen and M.B. Moffett, "A Model for Parametric Sonar Radiator Design," Naval Underwater Systems Center, Technical Memorandum No. PA4-229-71 (Sept. 1971).
7. R.L. Rolleigh, "Difference Frequency Pressure Within the Interaction Region of a Parametric Array," J. Acous. Soc. Am. 58, 964 -971 (1975).
8. R.H. Mellen, "A Nearfield Model of the Parametric Radiator," Naval Underwater Systems Center, Technical Memorandum No. PA4-230.75, December 1975.
9. R.H. Mellen and M.B. Moffett, "Numerical Method for Calculating the Nearfield of a Parametric Acoustic Source," J. Acous. Soc. Am. 61, S83 (A) (1977).
10. R.J. Bobber, Underwater Electroacoustic Measurements (U.S. Government Printing Office, Washington, D.C. 1970).
11. M.B. Moffett, Private Communication, June 1977.

APPENDIX A

In this appendix is supplied for reference a FORTRAN listing of the main program and required subprograms used to evaluate the Muir-Willette model. The original model is described in Reference 1. Modifications made by the author are noted in the comments at the beginning of the listing.

```
      PROGRAM WILLETT(INPUT,OUTPUT)
C     THIS PROGRAM COMPUTES THE AXIAL SOURCE LEVEL OF A PARAMETRIC
C     ARRAY BY THE VOLUME INTEGRATION METHOD.  THE PROGRAM WAS
C     ORIGINALLY WRITTEN BY J. G. WILLETTE AT APPLIED RESEARCH
C     LABORATORIES, THE UNIVERSITY OF TEXAS AT AUSTIN.  SUBSTANTIAL
C     MODIFICATIONS WERE SUBSEQUENTLY MADE BY J. C. LOCKWOOD.
C     THESE MODIFICATIONS INCLUDE 1) THE INCLUSION OF A FINITE
C     AMPLITUDE TAPER FUNCTION, 2) REVISION OF THE INPUT PARAMETERS
C     TO SI UNITS, AND 3) APPLYING A SINH STRETCHING TO THE RANGE
C     VARIABLE TO REDUCE THE NUMBER OF INTEGRATION STEPS REQUIRED
C     FOR CONVERGENCE.
C
C     PROGRAM INPUT REQUIRES THREE CARD TYPES.  CARD TYPE 1 IS IN
C     (8E10.3) FORMAT AND REQUIRES FK1 AND FK2, TWO PRIMARY
C     FREQUENCIES IN HZ, P1 AND P2, TWO RMS PRIMARY SOURCE LEVELS
C     IN DB RE 1 MICROPASCAL AT 1 M, A, PISTON RADIUS IN METERS,
C     TEMP, WATER TEMPERATURE IN DEGRES CELSIUS, AND S, SALINITY
C     IN PARTS PER THOUSAND.
C
C     CARD TYPE 2 IS IN FORMAT (2I10,2F10.0) AND REQUIRES IJ, A
C     CONVERGENCE TEST CONTROL, M, THE RANGE INTEGRATION STEP
C     CONTROL, XNN, THE AZIMUTH INTEGRATION STEP CONTROL, AND
C     BOVERA, THE PARAMETER OF NONLINEARITY, AND DEPTH THE
C     PROJECTOR DEPTH IN METERS.  IJ TAKES THE VALUES
C     1 AND 2.  IF IT IS 1, A CONVERGENCE TEST IS PERFORMED WHICH
C     CONSISTS OF ADDING 10 TO THE NUMBER OF RANGE INTEGRATION STEPS
C     AND RECOMPUTING SLD.  THE DIFFERENCE IS OUTPUT AS DELTA AND IS
C     A MEASURE OF THE CONVERGENCE. M IS THE NUMBER OF STEPS IN THE
C     RANGE INTEGRATION.  XNN IS THE NUMBER OF AZIMUTH STEPS PER
C     DEGREE OF MAIN LOBE HALFWIDTH.  THE INTEGRATION IS CARRIED OUT
C     BETWEEN THE FIRST INFINITIES OF THE PRIMARY BEAM MAIN LOBE.
C
C     CARD TYPE 3 IS OF FORMAT (E10.3) AND REQUIRES A RANGE IN METERS.
C
C     A ZERO VALUE FOR FK1 ON CARD TYPE ONE TERMINATES THE PROGRAM.
C     OTHERWISE, CARD TYPE 1 IS ALWAYS FOLLOWED BY ONE CARD TYPE 2.
C     THEN, AS MANY CARDS TYPE 3 AS DESIRED ARE INPUT.  A ZERO
C     RANGE SIGNALS A NEW CASE, AND A NEW CARD TYPE 1 IS READ.
C
C                                     J. C. LOCKWOOD
C                                     17 MAY 1977
      COMMON A1PA2,BK1(400),COSX(400),SINX(400),R,KD,IFSW,ITIME,OUTR(200CTH00010
     *0),OUTI(2000),RO,A,K1,K2,RMAX,ALPHAD,P1,P2,BOVERA,SMRD,SIG,CO  , CTH00020
     1RFL,XYZ,ZU
      DIMENSION X(34)
      REAL K1,K2,KD                                                     CTH00070
      REAL J0,J1                                                        CTH00080
      DATA  X/4HWD  ,4H    ,4HSM R,4HD   ,4HP1  ,4H    ,4HK1  ,4H    ,  CTH00100
     *4HK2  ,4H    ,4HA   ,4H    ,4HRHOD,4H    ,4HCD  ,4H    ,4HB/A ,  CTH00110
     *4H    ,4HHWID,4HTH  ,4HKD  ,4H    ,4HALPH,4HA1  ,4HALPH,4HA2  ,  CTH00120
     *4HP2  ,4H    ,4HALPH,4HAD  ,4HF1  ,4H    ,4HF2  ,4H    /          CTH00130
      ASINH(X)=ALOG(X+(X*X+1.)**.5)                                     CTH00140
      PI=3.141592 $ TUPI=2.0*PI                                         CTH00160
C     THE FOLLOWING STATEMENT READS CARD TYPE 1
  999 READ 2,FK1,FK2,P1,P2,A,RHOO,TEMP,S
      IF(FK1.EQ.0.0)GO TO 12                                            CTH00190
      P1=P1-96.2227                                                     CTH00200
```

```
            P2=P2-96.2227                                                        CTH00230
            A=A*100.                                                             CTH00240
            RHOO=RHOO/1000.                                                      CTH00250
C           THE FOLLOWING STATEMENT READS CARD TYPE 2
            READ 301,IJ,M,XNN,BOVERA,DEPTH                                       CTH00260
            PRESS=DEPTH*.097+1.
      301   FORMAT(2I10,3F10.0)
            MM=M
            FKD=ABS(FK1-FK2)                                                     CTH00280
            WD=TUPI*FKD $ CO=SPEED(S,TEMP,PRESS)                                 CTH00290
            CO=CO $ RMAX=SMRO $ RHOO=RHOO                                        CTH00300
            K1=TUPI*FK1/CO $ K2=TUPI*FK2/CO                                      CTH00310
            SMRO=(K1+K2)/2.*(A/2.)**2                                            CTH00320
            KD=TUPI*ABS(FK1-FK2)/CO                                              CTH00330
            HWIDTH=ASIN(3.83170571/A/(K1+K2)*2.)/.0174533
            ALPHA1=ALF(S,TEMP,FK1/1000.,PRESS)
            ALPHA2=ALF(S,TEMP,FK2/1000.,PRESS)
            ALPHAD=ALF(S,TEMP,FKD/1000.,PRESS)                                   CTH00360
      401   FORMAT(/,5X,"S = ",F4.1," PPT",5X,"TEMP = ",F5.2," C",5X,/)          CTH00380
  2         FORMAT(8E10.3)                                                       CTH00390
            REF=91.44                                                            CTH00400
  9         FORMAT("1PARAMETERS (CONVERTED TO CGS ; P1 AND P2 ARE PEAK RE 1 MI
           1CROBAR AT 1 YD):",/,(/,8X,2A4,2H= ,E16.9))
  300       FORMAT(7,9X,2HR ,29X,2HPD,30X,3HSLD,17X,5HDELTA,20X,1HM,/)
            PRINT 13
      13    FORMAT(/////)
            PRINT 9,X(1),X(2),WD,X(3),X(4),SMRO,X(5),X(6),P1,                    CTH00430
           ?X(27),X(28),P2,X(31),X(32),FK1,X(33),X(34),FK2,                      CTH00440
           ?X(7),X(8),K1,X(9),X(10),K2,X(11),X(12),A,X(13),X(14),RHOO,           CTH00450
           ?X(15),X(16),CO,X(17),X(18), BOVERA,X(21),X(22),KD,                   CTH00460
           ?X(23),X(24),ALPHA1,X(25),X(26),ALPHA2,X(29),X(30),ALPHAD,            CTH00470
           ?X(19),X(20),HWIDTH                                                   CTH00480
            PRINT 401,S,TEMP                                                     CTH00370
            PRINT 300
  1         FORMAT(T115,E10.3)
            P1 = 10.0**(P1/20.0)                                                 CTH00490
            P2 = 10.0**(P2/20.0)                                                 CTH00500
            C=-1.0*WD*WD*REF*REF  *P1*P2*(1.0+BOVERA*0.5)                        CTH00510
            C=C/(  2.0 *   RHOO*CO**4)                                           CTH00520
            A1PA2=ALPHA1+ALPHA2                                                  CTH00530
            A1PA2=EXP(-A1PA2)                                                    CTH00540
            T=0.0                                                                CTH00550
            N=HWIDTH*XNN                                                         CTH00560
            J=N/2*2$IF(J.NE.N)N=N+1                                              CTH00570
            D = 0.0174533/XNN                                                    CTH00580
            NP1=N+1                                                              CTH00590
            DO 4 K=1,NP1                                                         CTH00600
            COSX(K)=COS(T)                                                       CTH00610
            SINX(K)=SIN(T)                                                       CTH00620
            IF(SINX(K).NE.0.0)GOTO 31                                            CTH00630
  30        BK1(K)=BK2   =1.0                                                    CTH00640
            GO TO 4                                                              CTH00650
  31        CONTINUE                                                             CTH00660
            BARG=K1*A*SINX(K) $ BK1(K)=J1(BARG)                                  CTH00670
            BARG=K2*A*SINX(K) $ BK2   =J1(BARG)                                  CTH00680
            BK1(K)=4.0*BK1(K)*BK2   /(K1*K2*A*A*SINX(K))/SINX(K)                 CTH00690
  4         T=T+D                                                                CTH00700
```

```
 200    FORMAT(1X,20F5.3)                                          CTH00710
 C      THE FOLLOWING STATEMENT READS CARD TYPE 3
  100   READ 2,RO                                                  CTH00720
        RO=RO*100.                                                 CTH00730
        IF(RO.EQ.0.) GO TO 999                                     CTH00740
        M=MM                                                       CTH00750
      3 IX1 = IJ                                                   CTH00760
        UMAX=ASINH(RO/2./SMRO)                                     CTH00770
  40    XM=M                                                       CTH00780
        PRINT1,XM
        DELTA=UMAX/XM                                              CTH00800
        U=0.                                                       CTH00810
        MP1=M+1                                                    CTH00820
        DO 5 L=1,MP1                                               CTH00830
        P=SMRO*2.*SINH(U)                                          CTH00840
        IF(L.EQ.MP1) R=RO                                          CTH00850
        IFSW=1                                                     CTH00860
        ITIME=1                                                    CTH00870
        RADIAN = HWIDTH*0.0174533                                  CTH00880
        CALL INTEGR(OUTR(L),0.0,RADIAN    ,N)                      CTH00890
        IFSW=2                                                     CTH00900
        ITIME=1                                                    CTH00910
        CALL INTEGR(OUTI(L),0.0,RADIAN    ,N)                      CTH00920
  5     U=U+DELTA                                                  CTH00930
        IFSW=3                                                     CTH00940
        ITIME=1                                                    CTH00950
        CALL INTEGR(AR,0.0,UMAX,P)                                 CTH00960
        IFSW=4                                                     CTH00970
        ITIME=1                                                    CTH00980
        CALL INTEGR(AI,0.0,UMAX,M)                                 CTH00990
        AR=AR*C $ AI=AI*C                                          CTH01000
        AB=SQRT(AR**2+AI**2)                                       CTH01010
        ADB=20.0*ALOG10(AB)+97.                                    CTH01020
        IF (IX1.EQ.2) GOTO 8                                       CTH01030
  7     IX1=2                                                      CTH01040
        XLDB=ADB                                                   CTH01050
  70    M=M+10                                                     CTH01060
        GO TO 40                                                   CTH01070
  8     DELTA=(XLDB-ADB)                                           CTH01080
        XLDB=ADB                                                   CTH01090
        RO=RO/100.
        ADB=ADB+20.*ALOG10(RO)
        PRINT 10,RO,AR,AI,ADB,DELTA                                CTH01110
  10    FORMAT(2X,E16.9,5X,E16.9,3H + ,E16.9,2H I,5X,E16.9,5X,E16.9)  CTH01160
        GO TO 100                                                  CTH01190
  12    PRINT 5252                                                 CTH01200
 5252   FORMAT(1H1)                                                CTH01210
        END                                                        CTH01220
```

```
SUBROUTINE COSIN       73/74    OPT=1                  FTN 4.6+428         77/07/08. 10.52.40          PAGE      1

                 SUBROUTINE COSIN(X,SX,CX)
                 SX=SIN(X)
                 CX=COS(X)
                 RETURN
                 END
```

```
FUNCTION J1          73/74    OPT=1                        FTN 4.6+428        77/07/08. 10.52.40        PAGE     1

                                                                         CTH01570
             REAL FUNCTION J1(X)
             Y=0.                                                        J1 00030
             A=0.                                                        J1 00040
             T=0.                                                        J1 00050
             Z=X                                                         J1 00060
             X=ABS(X)                                                    J1 00070
             IF(X.LE.3.)GO TO 5                                          J1 00080
             IF(X.GT.3.)GO TO 10                                         J1 00090
             GO TO 15                                                    J1 00100
       5     X=Z                                                         J1 00110
             Y=X/3.                                                      J1 00120
             A=.5-.56249985*(Y**2)+.21093573*(Y**4)-.03954289*(Y**6)     J1 00130
             A=(A+.00443319*(Y**8)-.00031761*(Y**10)+.00001109*(Y**12))*X J1 00140
             J1=A                                                        J1 00150
             GO TO 15                                                    J1 00160
      10     Y=3./X                                                      J1 00170
             F=.79788456+.00000156*Y+.01659667*(Y**2)+.00017105*(Y**3)   J1 00180
             F=F-.00249511*(Y**4)+.00113653*(Y**5)-.00020033*(Y**6)      J1 00190
             T=X-2.35619449+.12499612*(Y)+.00005650*(Y**2)-.00637879*(Y**3) J1 00200
             T=T+.00074348*(Y**4)+.00079824*(Y**5)-.00029166*(Y**6)      J1 00210
             J1=F*COS(T)/X**.5                                           J1 00220
             IF(Z.LT.0.)J1=-J1                                           J1 00230
      15     RETURN                                                      J1 00240
             END                                                         J1 00250
```

```
FUNCTION FTC        73/74    OPT=1                          FTN 4.6+428        77/07/08. 10.52.40        PAGE     1

                FUNCTION FTC(X)                                                         CTHD1230
                COMMON A1PA2,PK1(400),COSX(400),SINX(400),R,KD,IFSW,ITIME,OUTR(200CTHD1240
               *0),OUTI(2000),RO,A,K1,K2,RMAX,ALPHAD,P1,P2,BOVERA,SMRO,SIG,CO    ,  CTHD1250
               1RFL,XYZ,D
                DIMENSION DUM(1000)                                                     CTHD1270
                REAL KD                                                                 CTHD1280
                REAL K1,K2                                                              CTHD1290
                GO TO (10,20,30,40) IFSW                                                CTHD1300
         10     Q=R $ SIG=SIGMA(G)                                                      CTHD1310
                IF(SINX(ITIME).GE..00001) GO TO 12                                      CTHD1330
             11 IF(R.NE.RO) GO TO 22                                                    CTHD1340
                FTC=1.0/RO/(1.+(SIG/2.)**2)                                             CTHD1350
                RAD=KD*RO                                                               CTHD1360
                GO TO 13                                                                CTHD1370
             22 FTC=DUM(ITIME)=0.0                                                      CTHD1380
                GO TO 15                                                                CTHD1390
             12 RAD =SQRT((R              )**2+RO*RO-2.0*R*RO*(COSX(ITIME)))            CTHD1400
                FTC=BK1(ITIME)*EXP(-ALPHAD*RAD)/RAD*SINX(ITIME)/(1.+(SIG/2.)**2)
                RAD=KD*(RAD+R)                                                          CTHD1420
             13 CALL COSIN(RAD,SX,CX)                                                   CTHD1430
                DUM(ITIME)=FTC*SX                                                       CTHD1440
                FTC=FTC*CX                                                              CTHD1450
                GO TO 15                                                                CTHD1460
             20 FTC=DUM(ITIME)                                                          CTHD1470
         15     ITIME=ITIME+1                                                           CTHD1480
                RETURN                                                                  CTHD1490
             30 FUNC=A1PA2**(SMRO*2.*SINH(X))                                           CTHD1500
                FTC=OUTR(ITIME)*FUNC*SMRO*2.*COSH(X)                                    CTHD1510
                GO TO 15                                                                CTHD1520
             40 FUNC=A1PA2**(SMRO*2.*SINH(X))                                           CTHD1530
                FTC=OUTI(ITIME)*FUNC*SMRO*2.*COSH(X)                                    CTHD1540
                GO TO 15                                                                CTHD1550
                END                                                                     CTHD1560
```

```
FUNCTION SPEED       73/74    OPT=1                        FTN 4.6+428        77/07/08. 10.52.40        PAGE     1

                 FUNCTION SPEED(S,T,P)                                                      ALS00010
           C SOUND SPEED IN CM/SEC                                                          ALS00020
           C S  SALINITY IN PARTS PER THOUSAND                                              ALS00030
           C T TEMP. IN DEGREES C                                                           ALS00040
           C P  PRESSURE IN KG/CM**2  1 ATM FOR G=980 CM/SEC**2                             ALS00050
                 VT=4.5721*T-4.4532E-2*T**2-2.6045E-4*T**3+7.9851E-6*T**4                   ALS00060
                 VP=1.60272E-1*P+1.0268E-5*P**2+3.5216E-9*P**3-3.3603E-12*P**4              ALS00070
                 VS=1.39799*(S-35)+1.69202E-3*(S-35)**2                                     ALS00080
                 VSTP=(S-35)*( -1.244E-2*T+7.7711E-7*T**2+7.7016E-5*P-1.2943E-7*P**ALS00090
                12+3.158E-8*P*T+1.579E-9*P*T**2)+ P*(-1.8607E-4*T+7.4812E-6*T**2+4.ALS00100
                15283E-8*T**3)+P**2*(-2.5294E-7*T+1.8563E-9*T**2)-P**3*1.9646E-10*TALS00110
                 SPEED=1449.14+VT+VP+VS+VSTP                                                ALS00120
                 SPEED=SPEED*100.                                                           ALS00130
                 RETURN                                                                     ALS00140
                 END                                                                        ALS00150
```

```
FUNCTION E1          73/74    OPT=1                    FTN 4.6+428         77/07/08. 10.52.40         PAGE     1

                    FUNCTION E1(X)
                    A=X
                    CALL EXPI(RES,A,AUX)
              C     EXPI IS IN THE IBM SCIENTIFIC SUBROUTINE PACKAGE (SSPLIB/UN=RAYFTN)
                    E1=RES
                    RETURN
                    END
```

```
FUNCTION ALF        73/74    OPT=1                    FTN 4.6+428         77/07/08. 10.52.40        PAGE     1

                FUNCTION ALF(S,T,F,P)                                                   ALS00010
      C         SMALL SIGNAL ABSORPTION COEFFICIENT IN NEPERS/CM                        ALS00020
      C         ONE NEPER IS 8.686 DB                                                   ALS00030
      C S -     SALINITY IN PARTS/THOUSAND                                              ALS00040
      C T -     TEMP IN DEGREES C                                                       ALS00050
      C F -     FREQ IN KHZ                                                             ALS00060
      C P -     PRESSURE KG/CM**2 = 1 ATM IF G=980 CM/SEC**2                            ALS00070
                IF(S.GT.0.0) GO TO 1                                                    ALS00080
                A = 6.0 - 1520.0/( T + 273.0 )                                          ALS00090
                FT=21.9*10.0**A                                                         ALS00100
                ALF=((2.34E-6*S*FT*F*F)/(FT*FT+F*F) + 3.38E-6*F*F/FT)*                  ALS00110
               1 (1.0-6.54E-4*P)                                                        ALS00120
                ALF=ALF/100 $ RETURN                                                    ALS00130
              1 A1=1.7760                                                               ALS00140
                A2=32.768                                                               ALS00150
                A3=6.54E-04                                                             ALS00160
                A4=0.018587                                                             ALS00170
                A5=0.026847                                                             ALS00180
                E=2.7182818285                                                          ALS00190
                CF=1.0936133E-05/(20.0*ALOG10(E))                                       ALS00200
                TEMP=T                                                                  ALS00210
                FT=21.9*10.0**((6.0*TEMP+118.0)/(TEMP+273.0))                           ALS00220
                FKHZ=F                                                                  ALS00230
                FKHZ2=FKHZ*FKHZ                                                         ALS00240
                FKHZ3=FKHZ*FKHZ2                                                        ALS00250
                ALFADB=(A1*FKHZ**1.5/(A2+FKHZ3))+((1.0-A3*P)/(1.0+A2/FKHZ3))*((A4       ALS00260
               **S*FT*FKHZ2/(FKHZ2+FT*FT))+A5*FKHZ2/FT)                                 ALS00270
                ALF=ALFADB*CF                                                           ALS00280
                RETURN                                                                  ALS00290
                END                                                                     ALS00300
```

```
SUBROUTINE INTEGR     73/74    OPT=1                    FTN 4.6+428        77/07/08. 10.52.40       PAGE     1

              SUBROUTINE INTEGR(X,BOT,TOP,INT)
              XINT=INT
              H=(TOP-BOT)/XINT
              X=FTC(BOT)
              W=4.0
              B=BOT+H
              N=INT-1
              DO 1 K=1,N
              A=FTC(B)
              A=A*W
              X=X+A
              B=B+H
        1     W=6.-W
              X=X+FTC(TOP)
              X=X*H/3.
              RETURN
              END
```

```
FUNCTION SIGMA       73/74    OPT=1                    FTN 4.6+428        77/07/08. 10.52.40        PAGE    1

            FUNCTION SIGMA(Q)                                                     TAP00010
      C                                                                           TAP00020
      C     MODIFIED BERKTAY LEAHY SIGMA WITH DIRECTIVITY                         TAP00030
      C                                                                           TAP00040
            COMMON A1PA2,BK1(400),COSX(400),SINX(400),R,KD,IFSW,ITIME,OUTR(200TAP00050
           *0),OUTI(2000),RO,A,K1,K2,SMRO,ALPHAD,P1,P2,BOVERA,RMAX,SIG,CO   ,  TAP00060
           1RFL,XYZ,D                                                             TAP00070
            REAL K1,K2,KD                                                         TAP00080
            RRAYL=2.*RMAX                                                         TAP00090
            EPS=(P1+P2)/(CO**2)                                                   TAP00100
            BETA=1.+BOVERA/2.                                                     TAP00110
            AK=(K1+K2)/2.                                                         TAP00120
            ALPHO=-ALOG(A1PA2)                                                    TAP00130
            BEK=BETA*EPS*AK*91.44                                                 TAP00140
            IF(Q.GT.RRAYL) GO TO 10                                               TAP00160
            SIGMA=BEK/(ALPHO*RRAYL)*(1.-EXP(-ALPHO*R))                            TAP00170
            RETURN                                                                TAP00180
       10   D2=BK1(ITIME)                                                         TAP00190
            IF(D2.LT.0.) D2=-D2                                                   TAP00200
            D=SQRT(D2)                                                            TAP00210
            IF(ITIME.NE.1) GOTO1                                                  TAP00220
            SIGMAO=BEK/(ALPHO*RRAYL)*(1.-EXP(-ALPHO*RRAYL))                       TAP00230
            X1=ALPHO*Q                                                            TAP00240
            XO=ALPHO*RRAYL                                                        TAP00250
            FACT =(E1(XO)-E1(X1))                                                 TAP00260
        1   SIGMA=FACT*D*BEK+SIGMAO                                               TAP00270
            RETURN                                                                TAP00280
            END                                                                   TAP00290
```

APPENDIX B

In this appendix is supplied for reference a FORTRAN listing of the main program and required subprograms used to evaluate the Lockwood model. A description of the model may be found in Reference 5.

This program has also been implemented on a programmable calculator (Texas Instruments SR-52).

```
PROGRAM HORN        73/74   OPT=1                         FTN 4.6+428        77/07/08. 10.48.41        PAGE    1

            PROGRAM HORN(TAPE5,TAPE6)
      C     THIS PROGRAM CALCULATES THE AXIAL SOURCE LEVEL OF A PARAMETRIC
      C     TRANSMITTING ARRAY BY APPLYING GEOMETRICAL CORRECTION FACTORS
      C     TO LEVELS BASED ON THE 1971 MELLEN-MOFFETT THEORY.  A FACTOR
      C     IS APPLIED ONLY TO A PORTION OF THE INTERACTION RANGE AND IT IS
      C     NECESSARY THAT ATTENUATION IN THIS PORTION BE INSIGNIFICANT IF THE
      C     OBSERVATION POINT IS IN THE NEARFIELD.
      C
      C     THE INPUTS ARE SO FORMATTED THAT THE SAME INPUT FILE MAY BE
      C     USED FOR BOTH WILLETT AND HORN.   THEREFORE, CERTAIN VARIABLES,
      C     SPECIFICALLY IJ, RHO, M, XNN, AND BOVERA, ARE DUMMYS.  FOR
      C     GENERAL COMPATIBILITY, THE INPUT SHOULD BE PREPARED FOLLOWING THE
      C     INSTRUCTIONS FOR WILLETT.
      C
      C     FK1 AND FK2 ARE IN HZ, SL1 AND SL2 ARE RMS RE 1 MICROPASCAL AT 1 M, A
      C     IS RADIUS IN METERS,TEMP IS IN DEGREES CELSIUS, AND DEPTH IS IN
      C     METERS.
            EXTERNAL FTC
            COMMON TUARD, DSR, CHI                                          NFI00020
            REAL LSD                                                        NFI00030
            NAMELIST/INPUTS/FK1,FK2,SL1,SL2,A,TEMP,S
            ARSINH(X)=ALOG(X+(X*X+1.)**.5)                                  NFI00040
            PI=3.14159265                                                   NFI00050
        999 READ(5,2)FK1,FK2,SL1,SL2,A,RHO,TEMP,S
            IF(FK1.EQ.0.)GO TO 12                                           NFI00070
            READ(5,301)IJ,M,XNN,BOVERA,DEPTH
            PRESS=DEPTH*.097+1.
            WRITE(6,INPUTS)
          2 FORMAT(8E10.3)                                                  NFI00090
            FOOVF=(FK1+FK2)/ABS(FK1-FK2)/2.                                 NFI00100
            FO=(FK1+FK2)/2./1000.                                           NFI00110
            ALPHA=ALF(S,TEMP,FO,PRESS)                                      NFI00120
            CO=SPEED(S,TEMP,PRESS)/100.                                        NFI00
            RO=(FK1+FK2)*2.*PI/CO*(A/2.)**2                                 NFI00140
            RO=RO/.9144                                                     NFI00150
            SPL=(SL1+SL2)/2.-96.2227                                        NFI00160
        301 FORMAT(2I10,3F10.0)
            CO=CO*100.                                                      NFI00190
        100 READ(5,102) R
        102 FORMAT(F11.4)                                                   NFI00210
            IF(R.EQ.0.)GO TO 999                                            NFI00220
            R=R/.9144                                                       NFI00230
            DSR=1./FOOVF                                                    NFI00240
            TUARD=2.*RO*91.44*ALPHA                                         NFI00250
            UMAX=ARSINH(R/RO)                                               NFI00260
            EPS=10.**(SPL/20.)/CO/CC                                        NFI00270
            AK=3.83*FO                                                      NFI00280
            CHI=3.5*EPS*AK                                                  NFI00290
            USMRD=ARSINH(FOOVF)                                             NFI00300
            CALL FACTOR(FAC,ICASE,R,RO,FOOVF)                               NFI00310
            IF(ICASE.LE.2) GO TO 500                                        NFI00320
            CALL INTGRT(FTC,ROINT,0.,UMAX,30)                               NFI00330
            UTST=UMAX
            PE=FAC*ROINT*CHI/2.*DSR*DSR                                     NFI00340
            EXINT=0.                                                        NFI00350
            GOTO 600                                                        NFI00360
        500 CALL INTGRT(FTC,ROINT,0.,US*RO,30)                              NFI00370
```

```
PROGRAM HORN        73/74    OPT=1                    FTN 4.6+428        77/07/08. 10.48.41        PAGE     2

              UTST=USMRO
              CALL INTGRT(FTC,EXINT,USMRO,UMAX,30)                                     NFI00380
              PE=(FAC*ROINT+EXINT)*CHI/2.*DSR*DSR                                      NFI00390
        600   CONTINUE                                                                 NFI00400
              SPLD=SPL-20.*ALOG10(R)+20.*ALOG10(PE)+97.                                NFI00410
              CHI=1.E-4
              TUARO=1.E-4
              CALL INTGRT(FTC,TSTINT,0.,UTST,30)
              IF(TSTINT/ROINT.GE..89.OR.FAC.LT.1.22) GO TO 103
              WRITE(6,110)
        110   FORMAT("WARNING: SIGNIFICANT ATTENUATION IN REGION TO WHICH FACTOR
             1IS APPLIED")
        103   R=R*.9144                                                                NFI00420
              SPLD=SPLD+20.*ALOG10(R)
              PE=20.*ALOG10(PE)                                                        NFI00430
              WRITE(6,109) R,SPLD,PE
        109   FORMAT(" R=",F11.4,"SLD=",F11.4,"PARAMETRIC EFFICIENCY=",F11.4)
              WRITE(6,112)R,ICASE,FAC
        112   FORMAT("R=",F11.4,"ICASE=",I1,"FAC=",F11.4)                             NFI00470
              GO TO 100                                                                NFI00480
        12    CONTINUE                                                                 NFI00490
              END                                                                      NFI00500
```

```
FUNCTION FTC        73/74    OPT=1                  FTN 4.6+428       77/07/08. 10.48.41        PAGE     1

                    FUNCTION FTC(U)                                   FTC00010
                    COMMON TUARO,DSR,CHI                              FTC00020
                    A=SINH(U)                                         FTC00030
                    B=DSR*A                                           FTC00040
                    C=-TUARO*A                                        FTC00050
                    D=CHI*U/2.                                        FTC00060
                    FTC=EXP(C)/(1.+D**2)                              FTC00070
                    FTC=FTC*SQRT((1.+A*A)/(1.+B*B))                   FTC00080
                    RETURN                                            FTC00090
                    END                                               FTC00100
```

```
FUNCTION ALF        73/74    OPT=1                          FTN 4.6+428        77/07/08. 10.48.41        PAGE    1

           FUNCTION ALF(S,T,F,P)                                                 ALS00010
      C    SMALL SIGNAL ABSORPTION COEFFICIENT IN NEPERS/CM                      ALS00020
      C    ONE NEPER IS 8.686 DB                                                 ALS00030
      C S - SALINITY IN PARTS/THOUSAND                                           ALS00040
      C T - TEMP IN DEGREES C                                                    ALS00050
      C F - FREQ IN KHZ                                                          ALS00060
      C P - PRESSURE KG/CM**2 = 1 ATM IF G=980 CM/SEC**2                         ALS00070
           IF(S.GT.0.0) GO TO 1                                                  ALS00080
           A = 6.D - 1520.D/( T + 273.D )                                        ALS00090
           FT=21.9*10.D**A                                                       ALS00100
           ALF=((2.34E-6*S*FT*F*F)/(FT*FT+F*F) + 3.38E-6*F*F/FT)*                ALS00110
          1 (1.D-6.54E-4*P)                                                      ALS00120
           ALF=ALF/100 $ RETURN                                                  ALS00130
         1 A1=1.776D                                                             ALS00140
           A2=32.768                                                             ALS00150
           A3=6.54E-04                                                           ALS00160
           A4=0.018587                                                           ALS00170
           A5=0.026847                                                           ALS00180
           E=2.7182818285                                                        ALS00190
           CF=1.0936133E-05/(20.D*ALOG10(E))                                     ALS00200
           TEMP=T                                                                ALS00210
           FT=21.9*10.D**((6.D*TEMP+118.D)/(TEMP+273.D))                         ALS00220
           FKHZ=F                                                                ALS00230
           FKHZ2=FKHZ*FKHZ                                                       ALS00240
           FKHZ3=FKHZ*FKHZ2                                                      ALS00250
           ALFADB=(A1*FKHZ**1.5/(A2+FKHZ3))+((1.D-A3*P)/(1.D+A2/FKHZ3))*((A4  ALS00260
          **S*FT*FKHZ2/(FKHZ2+FT*FT))+A5*FKHZ2/FT)                               ALS00270
           ALF=ALFADB*CF                                                         ALS00280
           RETURN                                                                ALS00290
           END                                                                   ALS00300
```

```
SUBROUTINE INTGRT      73/74    OPT=1                          FTN 4.6+428          77/07/08. 10.48.41          PAGE      1

                SUBROUTINE INTGRT(FTC,X,BOT,TOP,INT)                                     CIN00010
          C********27 MARCH 1975****************************************                  CIN00020
                EXTERNAL FTC                                                              CIN00030
                XINT=INT                                                                  CIN00040
                H=(TOP-BOT)/XINT                                                          CIN00050
                X=FTC(BOT)                                                                CIN00060
                W=4.                                                                      CIN00070
                B=BOT+H                                                                   CIN00080
                N=INT-1                                                                   CIN00090
                DO 1 K=1,N                                                                CIN00100
                A=FTC(B)                                                                  CIN00110
                A=A*W                                                                     CIN00120
                X=X+A                                                                     CIN00130
                B=B+H                                                                     CIN00140
          1     W=6.-W                                                                    CIN00150
                X=X+FTC(TOP)                                                              CIN00160
                X=X*H/3.                                                                  CIN00170
                RETURN                                                                    CIN00180
                END                                                                       CIN00190
```

```
SUBROUTINE FACTOR      73/74    OPT=1                       FTN 4.6+428        77/07/08. 10.48.41        PAGE     1

              SUBROUTINE FACTOR(FAC,ICASE,R,RO,FOOVF)
              ROMIN=RO/FOOVF
              SMRO=RO*FOOVF
              RC=(SMRO/2.)*(-1.+SQRT(1.+4.*R/SMRO))
              IF(R.GE.2.*SMRO) ICASE=1
              IF(R.LT.2.*SMRO) ICASE=2
              IF(R.LT.SMRO) ICASE=3
              IF(R.LT.RO+ROMIN) ICASE=4
              IF(R.LT.RO) ICASE=5
              IF(R.LT.ROMIN) ICASE=6
              GO TO (10,20,30,40,50,60) ,ICASE
        10    FAC=R/SMRO*ALOG(R/(R-SMRO))
              RETURN
        20    FAC=R/SMRO*(ALOG(R/(R-RC))+(SMRO-RC)/RC)
              RETURN
        30    FAC=ALOG(R/(R-RC))+SMRO/R*(R-RC)/RC
              RETURN
        40    FAC=ALOG(R/ROMIN)-(R-RO)**2/R/ROMIN+1.
              RETURN
        50    FAC=ALOG(R/ROMIN)+1.
              RETURN
        60    FAC=R/ROMIN
              RETURN
              END
```

```
FUNCTION SPEED      73/74   OPT=1                          FTN 4.6+428        77/07/08. 10.48.41        PAGE     1

          FUNCTION SPEED(S,T,P)                                                 ALS00010
    C SOUND SPEED IN CM/SEC                                                     ALS00020
    C S  SALINITY IN PARTS PER THOUSAND                                         ALS00030
    C T TEMP. IN DEGREES C                                                      ALS00040
    C P  PRESSURE IN KG/CM**2  1 ATM FOR G=980 CM/SEC**2                        ALS00050
          VT=4.5721*T-4.4532E-2*T**2-2.6045E-4*T**3+7.9851E-6*T**4              ALS00060
          VP=1.60272E-1*P+1.0268E-5*P**2+3.5216E-9*P**3-3.3603E-12*P**4         ALS00070
          VS=1.39799*(S-35)+1.69202E-3*(S-35)**2                                ALS00080
          VSTP=(S-35)*( -1.244E-2*T+7.7711E-7*T**2+7.7016E-5*P-1.2943E-7*P**ALS00090
         12+3.158E-8*P*T+1.579E-9*P*T**2)+ P*(-1.8607E-4*T+7.4812E-6*T**2+4.ALS00100
         15283E-8*T**3)+P**2*(-2.5294E-7*T+1.8563E-9*T**2)-P**3*1.9646E-10*TALS00110
          SPEED=1449.14+VT+VP+VS+VSTP                                           ALS00120
          SPEED=SPEED*100.                                                      ALS00130
          RETURN                                                                ALS00140
          END                                                                   ALS00150
```